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AN OPTIMIZATION MODEL FOR INVESTIGATING ALTERNATIVE RESEARCH AND DEVELOPMENT PROGRAMS OF THE U.S. ARMY

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An Optimization Model for Investigating Alternative Research and Development Programs of the U.S. Army

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I. INTRODUCTION

The information processing capacity of any one man is limited. Faced with potentially enormous quantities of data pertaining to a decision problem, the task of the decision maker is to select the significant information from the trivial and to identify an appropriate course of action. However, even the identification phase of this process is a difficult task when the problem is as large as that of budgeting the research and development program of the U. S. Army. Narrowing the scope of the problem to one of selecting a budget for a particular system under development makes the problem more manageable, but the impact of this selection on the program as a whole may not be readily visible. With limited resources a decision on a budget for one system necessarily affects all the others. The decision problem then becomes one of identifying what should be sacrificed if any system is to be increased. In an R & D program as large as that of the Army's, the alternatives are almost countless and the time available for considering the problem is limited.

The Computer Assisted Research and Development Budget Optimization Model (CARDBOMB) is a cost-constrained, value maximization model which considers the interactions of the budgets of all the projects in the R & D program. It adds insight to the question; "Based on the information gathered during the planning phase concerning the value and cost of each proposed project, how should X billion dollars be distributed among these projects?"

For development programs which are at or beyond the concept formulation stage of development, the model uses optimization techniques for providing insight into this question. The variables considered in the model are:

1. The value of a system (the end product of a development plan); a function of time, need, useful life, uncertainty and dollar costs.

2. The cost of a system; a function of development, procurement and operating costs, performance characteristics and operational readiness dates, time and uncertainty.

The model also deals with basic research and exploratory development projects, i.e., those not directly associated with a program which has reached the concept development stage. Optimization methods are not used for these projects, but decision rules are suggested for investigating alternative budgets.

Methods for quantifying the value of a system are discussed at length. Although the meaning of the terms "value" and "system" are dealt with more explicitly later, it should prove useful to introduce them here. An R & D system is the end product that is expected to result from one or more projects, e.g., the goal of a system's development plan. In the hardware area the Cheyenne helicopter or the MBT 70 tank are examples of systems. In a non-hardware area such as research in human performance, a system is the specific knowledge that is expected to be gained from one or more research projects. For example a system in the category of human performance might be termed "extending the endurance limits of the individual soldier," consisting of a number of research or test projects. Systems are then categorized by general type, e.g., air mobility, missiles, human performance, etc. Within these categories experts are asked to use their own subjective value judgement in rating the relative importance they place on the systems in their category. Methods are then devised for transforming the interval scale of measurement scores of each category onto an interval scale for the entire R & D program so that the value of a system in one category can be related to the value of a system in another. Thus value, rather than being some intrinsic property of a system, is a perceptive notion

derived by considering what the system is designed to accomplish, and how much this capability is required.

A. FORMULATION OF THE RESEARCH AND DEVELOPMENT PROGRAM

Before beginning the development of the model, it should prove useful to briefly discuss how Program 6, Research, Development, Test and Evaluation (RDTE), of the Army budget is formulated.[1]

Requirements for new weapon systems, and therefore R & D projects, are identified by a number of organizations. First, the intelligence community makes known the current and projected capabilities of potential enemies. Second, the studies conducted by the Combat Developments Command and other agencies concerning the organization and tactical employment of the Army of the future identify areas in which weapons technology must be advanced. Additionally, technological advances have their own way of creating needs for new systems. For example, a breakthrough in research on tank engines may lead to the decision that the most cost-effective step that can be taken is to develop a new tank. This ties in closely with a fourth way that needs arise, technological obsolescence. Some systems, designed with the technology of the past, have lost much of their initial value due to counter developments by potential enemies.

All of these needs, or requirements, are channeled into the Army's in-house R & D community for validation of the need and investigation of possible alternatives. This process, which includes extensive investigation of the new technologies that would have to be developed to support the various alternatives, is called the concept formulation stage. Finally the point is reached where a development plan

[1]For a more detailed discussion of the Army's R & D organization and procedures, as well as the overall Department of Defense management of R & D, see Sanders [ref. 1].

item projects in Program 6 of the Five Year Defense Plan (FYDP), a planning and budgeting document maintained by the Army's Chief of Research and Development (CRD). It should be noted at this point that not all of the more than 600 line item projects in Program 6 are directly related to a specific system. Many of them pertain to overhead of the R & D in-house community (Sub-Program 6.5 — Management and Support) as well as basic research (Sub-Program 6.1) not directly associated with a particular system.[4] Program 6, like all the Army budget programs, might be called a living document. As was mentioned, new projects are added every time a new DCP is approved. Additionally, within the bounds of the threshold points, DA may often alter the funding levels of various projects. However at some point in time during the annual budget cycle, the CRD submits the particular Program 6 that he recommends for inclusion in the Army budget to be submitted to DOD for approval and forwarding to the President. For the purposes of this paper, this five year funding schedule for all Program 6 projects <u>and</u> the funding schedules for each of them in the years beyond the FYDP up to the last year in which RDTE funds are planned will be called the <u>base case</u>.

B. THE PROBLEM: INVESTIGATING ALTERNATIVE BUDGETS

Once a Program 6 base case has been recommended by the Chief of Research and Development, the final decision on the program to be recommended to the President is far from reached. The Army's Budget Review Committee (BRC) and other top-level committees as the Secretary of the Army of the Chief or Staff may direct must then investigate how this base case fits in with other Army programs, and what adjustments might or must be made to insure compliance with national

[4]More detail concerning the content of Program 6 will be presented in Section II, C, "A Taxonomy of R & D Systems."

security objectives and the DOD fiscal guidance constraints. This is not to imply that these considerations are disregarded in arriving at the Program 6 base case. On the contrary, it was formulated throughout the year in an iterative fashion with just these considerations in mind. However, during the "budget crunch" months of October through December, difficult trade-off decisions must be made, and the BRC plays an increasingly important role.[5] In essence they must investigate alternative mixes between Army programs which in turn determine the level, or total budget constraint, of each. To do this with as much insight as possible in order to avoid setting arbitrary limits on the levels of programs, it is also necessary for them to investigate mixes within the programs. Unfortunately the time constraints of the PPBS cycle may limit this investigation substantially. It is not inconceivable to imagine that only the highest cost or critically important items get carefully investigated, while other projects in a program might have to experience something approaching an "across the board" percentage change, usually a reduction. While no empirical evidence is offered here to support this contention, it would appear logical that the more time available for identifying and investigating alternatives, the better the decision.

Ultimately a budget gets approved by the Secretary of the Army for forwarding to DOD, but the budgeting problem is still far from resolved. DOD continues to make Program Budget Decisions which are either accepted or rebutted by the Services. Additionally, either because the Office of Management and Budget has altered the budget constraint of DOD as a whole or because DOD wishes to investigate the alternative mixes between the Services, the Army may be directed to submit a new program constrained at some different level.

The sometimes severe time constraints on these important deliberations and the need for vast quantities of readily available information pertaining to individual

[5]Although the BRC is not the only agency making recommen[illegible]ions to the SA and COS concerning the budget, for simplicity this paper will refer [illegible]ly to them as the principal advisors.

programs has led the Office of the Assistant Vice Chief of Staff, Army (AVCSA) the Army's coordinating office for matters pertaining to the PPBS, to move toward automated management information systems. This paper is directed at assisting in this effort within the context of the existing decision problem and organizational structure. Six specific decision problems representing the range of options for altering the Program 6 budget are addressed. These are:

1. Should the funding of a system be reduced?
2. Should the funding of a system be increased?
3. Should the schedule of a system be slipped, freeing funds for a particular year? (Slipping is defined as delaying the start of a proposed development program, or cutting it off somewhere in mid-cycle with the intent of continuing it at a later date.)
4. Should a new system just finishing the concept development stage be added to the program?
5. Should a system be dropped from the program?
6. Should funds be added to or taken away from the total RDTE budget?

The extent of the six decision problems addressed by CARDBOMB shows that its potential users might be the planning staffs of the Director of the Army Budget, the BRC, the AVCSA or the CRD.

C. CONSIDERATIONS IN MODELING RESEARCH AND DEVELOPMENT

There are characteristics of R & D programs, both military and industrial, that make them particularly difficult to manage. A brief introduction to some of these problems is presented here so that the reader will be cognizant of them and follow more carefully how each of them are dealt with in the model. Chief among these difficulties is uncertainty.

The uncertainty of the need for a particular system, sometimes called scenario risk, is usually the most uncertain factor. The intelligence community might forecast

that by 1986 every Russian soldier will be equipped with a man-packed jet propulsion unit capable of moving him above ground at 30 knots for great distances. There may, however, be a considerable question as to the validity of the forecast. Additionally there may be uncertainty as to the best approach to counter this move. Finally, no one can state for sure that by 1986 the Russians will be a potential threat. Perhaps, if the future were known, the need might be greater in countering a gamma ray gun development in Albania.

The uncertainty of the availability date and ultimate performance characteristics of a weapon system undergoing development are termed technological uncertainty. Given the varying degrees of the state of the art in different technologies, it may become necessary to settle for less than the system's performance objectives formulated in its current DCP. On the other hand a major technological breakthrough might allow the achievement of far more value than is currently envisioned. Similarly, the technological development problems might take so long to resolve that, by the system's availability date, it has already been overtaken by events. For example, some counter R & D move by a potential enemy either now or in the future might seriously degrade the value of the system as currently perceived. This introduces the notion, to be explored in greater depth in Chapter 2, that the value of a completed system is not constant over time.

The third significant factor is cost uncertainty. Particularly during the early concept formulation stage, R & D and other important cost estimates might be far off the mark. Even as development of the system continues, PEMA and OMA cost projections still may prove to be significantly different than projected.[6]

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[6]Procurement of Equipment and Missiles, Army (PEMA) and Operation and Maintenance, Army (OMA) are two additional budget programs. Both the procurement and operation and maintenance costs are costs that must be considered with RDTE funds in the "develop or do not develop" type decisions.

Examples of the implications of these uncertain factors illuminate their interdependence. If for a given system, RDTE costs have been estimated too low, PEMA funds for this system and others might have to be transferred, thus lowering the total, overall value to be gained. If the need has been overstated and Russia never fields jet-propelled soldiers, then the value of our jet-propelled Russian barrier may be zero, not to mention the value lost from other systems that might have been developed with the same funds.

Another difficulty encountered in the modeling of R & D is its lack of a unit of measure; i.e., it is meaningless to talk about dollars per unit of R & D. What type of an R & D unit of output could be defined such that two million dollars would buy twice as many units as one million? The MARK TWAIN, a Leontif Input-Output model currently being used by DA in studying the force structure budgeting problem, has as a necessary input the cost per unit for Force X. The EXECUTIVE GUIDANCE/DECISION MODELS, an automated management information system also used in DA for studying the PEMA, OMA, manpower and force structure budgets, also require these linear cost estimating relationships.[7] The activity analysis structure of these two models makes them inappropriate for R & D, primarily because of this lack of a unit of measure of output.

It may be enlightening in this introduction to compare the purposes of these two models and the one proposed in this paper. The MARK TWAIN is primarily a costing model. The user inputs the force structure he is investigating and the model generates its cost. THE DEAN MACHINE, on the other hand, incorporates some built-in, parameterized decision rules for the alteration of the budgets of

[7]The reader acquainted with Army budgeting models will prob ly recognize this by its more familiar name, THE DEAN MACHINE, after its pr pal author, LTC A. M. R. Dean.

specific line items in the budget program the user is investigating. For example, the purchase of a 2½-ton truck might be the first priority for reduction in the PEMA budget, but only a five percent reduction can be absorbed. The user inputs the total budget constraint he is investigating for the PEMA program, and the model uses the decision rules to produce a new program constrained at this level. CARDBOMB has a similar objective. The user inputs a total RDTE budget constraint, and then based on one of a number of specific strategies he may wish to employ, a single, mathematically optimal alternative is presented which both maximizes the value of the entire program and meets the total budget constraint specified. Of course as has been stated, "value" will be defined more explicitly later.

Despite the problems posed by uncertainty, lack of a unit of measure and other factors, extensive efforts have been made to model R & D, both in the military and the industrial sectors. The primary emphasis, however, has been on project selection in the general field called capital budgeting. Project selection models have as their primary emphasis the decision problem faced when a new system is proposed. For the most part they are not concerned with incremental changes to the budgets of existing development programs. However some of these models could be very useful to the Army and are discussed further in the text.

There are, however, at least two models which to some degree do address the problem of determining optimal incremental budget changes. The first of these was developed by McGlauchlin [ref. 4] for the Honeywell Corporation. In brief, division managers were surveyed and asked to score on a numerical scale how they rated the relative profit potential of the R & D projects that were on-going or proposed. The scores were aggregated to arrive at a number representing the value of a project relative to the value of one currently being marketed. ...is gave the

planners a rough estimate of the expected profit potential of the projects rated. The scientific department was then asked what the earliest, latest and most likely completion times were for each project for various numbers of scientific teams assigned to it. All of these factors were then entered into a mathematical program which resulted in more efficient manpower utilization.

This example points out a significant difference between modeling industrial and military R & D programs (or any budget category, for that matter). The objective function in industrial models is generally uni-dimensional with one motive — maximize profit in dollars. In military R & D it is usually meaningless to assign dollar figures to the value of systems. A model called MEASURE I which was recently developed for DA by the Research Analysis Corporation (RAC) follows the same general formulation as the Honeywell model, but suggests a more appropriate way of quantifying the value of systems [ref. 5]. Many of the ideas that resulted in the model presented in this paper came from MEASURE I, and the author wishes to credit RAC for their work. However, the end product, CARDBOMB, is a model quite different from MEASURE I in its theoretical structure.

II. QUANTIFYING THE VALUE OF A RESEARCH AND DEVELOPMENT SYSTEM

Before a model of a complex program can be formulated, certain parameters have to be identified and measured. This chapter introduces the concept of the value of a system undergoing development; what it is and how it might be quantified.

A. THE CHARACTERISTICS OF VALUE

Terms such as value, utility, worth, effectiveness and cost can be quite vague if they are not carefully defined. This section introduces the meaning of value as used in this paper by first pointing out some of its characteristics.

First, value may be either objective or subjective. Objective value reflects some generally accepted measure like dollars. Subjective value, often called utility, can only indirectly be put in a market context. The value of an item becomes the equivalent of what a particular observer is willing to give up to get it. Another observer might feel differently about the exchange.

The values of two or more systems can also be commensurate or non-commensurate with each other. If the value of two items, each measured on different scales, can be transformed to the same scale, then they are said to be commensurate. For objective measures it is generally a simple matter to determine relations between value scales. If the value of item A is measured in dollars and item B in cents, one simply multiplies the value of B by 100 to make the two values commensurate. In the subjective measurement sense the value of two systems can be considered commensurate if the observer can relate the value of system A to that of B in terms meaningful to him. A pilot may say that as far as he is concerned, the overall

value the Army will get from the Cheyenne program is greater than the value of the Cobra. Since he can compare these, they are commensurate to him. The value of two systems are non-commensurate in the subjective sense if the observer cannot relate their values. The same pilot may have no feeling for the value of the Cheyenne program relative to one of the tank programs because of his lack of familiarity with the latter. Even if he were thoroughly familiar with both, the differences in their missions may not allow him to reasonably compare their values.

A third characteristic of value is concerned with how many attributes must be considered in its measurement. The value of a system is single attributed if it can be considered to accomplish only one significant objective, e.g., generate profit. It has multiple attributes if more than one significant objective must be considered in its determination. For example, it may move, shoot and communicate.

Lastly, measures of value must be time dated and scenario related. The value of a system is generally not considered to be constant over time. It cannot be expected that the Cheyenne will have the same value in 1976 as it will in 1986. Similarly, a system's value can be considerably different for two different scenarios, or operating environments, in which it might be placed. The value of the MBT 70 tank may vary considerably depending on whether it is performing a combat mission in the Vietnam Delta or the Fulda Gap.

Usually there is considerable disparity in the ease by which value can be measured for industrial projects and military systems. Risking a highly oversimplified generalization, it might be said that the measurements of value in business models are objective, single attributed and commensurate, while in the military they must be subjective, multi-attributed, and most likely only subsets of systems are commensurate, i.e., Cheyenne and Cobra.

B. OBSTACLES TO MEANINGFUL MEASURES OF VALUE

If the value of a military R & D program is characterized in this way, significant obstacles are raised in arriving at meaningful measures. CARDBOMB uses various methods to handle each of the obstacles discussed in this section.

If value is considered to be subjective, who is to be selected as the observer to render his judgement? Strictly theoretical models beg this issue and call him the decision maker. One might argue that this is the Secretary of the Army, but who can reasonably expect one man to have the necessary knowledge of each of the more than 600 projects, or even the time to think about it. Alternatively, some top level advisory board knowledgeable of all the systems might be surveyed, raising the additional problem of how all their replies should be aggregated, i.e., which one of them has the "right" answer.

The model builder is also faced with problems caused by the multiple attribute nature of value. Which measures of effectiveness should be selected? How are they to be measured, weighted and aggregated to arrive at a single value measurement? What indirect objectives, that is, extraneous to the primary mission of the program should be considered? A glance at the following incomplete list will show that these indirect objectives seldom appear in any cost-effectiveness study, but have a definite impact on the decision problem.

1. Support of an adequate R & D community. If the budget of System X is substantially reduced, forcing the bankruptcy of Company Y, how is the future R & D effort affected?

2. Political. If System X is dropped, what will result from Senator Smith's reaction?

3. Enemy R & D reaction. If we develop System X, what can we expect the Russians to do?

Another obstacle to the development of a useful model of the RDTE Program is the non-commensurability characteristic of value. To construct a model, value must be measured. To construct an optimization model, the value of each system must be measured on the same scale, and the type of scale used is significant. This point should become clearer in the next section.

Even within commensurate subsets of systems, i.e., those designed to accomplish generally similar objectives, additional obstacles arise to complicate the measurement of value. Most systems are not independent entities designed to operate in an environment all their own. More likely they achieve their value in a scenario in which they operate with other systems. Therefore the values of two or more systems may be interdependent rather than independent. The value of Tank System A might be considerably different when Tank System B is developed and when it is not.

Still more questions must be addressed in considering how to measure value. How should the three types of uncertainty be considered in the measurement of value? Should the value of a system be measured in the worst scenario envisioned, or the most likely? Should a conservative or optimistic view be taken in predicting the operating characteristics of the resulting system? And similarly, how should cost uncertainty be considered, since, as has been pointed out, an incorrect estimate may effect a loss in value to the program or other programs?

This list of obstacles illustrates the magnitude of the problem of measuring value. All of these considerations must be addressed in determining how well this or any other R & D model represents the real world. Following the development of the value measurement segment of this paper, we will return to this list to discuss how each obstacle was handled.

C. A TAXONOMY OF RESEARCH AND DEVELOPMENT SYSTEMS

In moving toward the goal of finding a method for making the value of as many RDTE projects commensurate as possible, a taxonomy, or classification scheme, must first be defined whereby " reasonably commensurate subsets" of systems can be identified. A reasonably commensurate subset will be loosely defined as a group of systems aimed toward the accomplishment of generally similar missions or objectives.

The most logical place to begin such a taxonomy is with the one currently used by the Army and defined in the Army Strategic Objectives Plan (ASOP). It identifies each RDTE line item project as belonging to one of the following 24 categories.

1. Air Mobility
2. Air Defense
3. Tank/Antitank
4. Communications
5. Surveillance, Target Acquisition, and Night Operations (STANO)
6. Surface Mobility
7. Indirect Fire
8. Infantry Weapons
9. Logistic Support
10. Electronic Warfare
11. Command and Control
12. Chemical/Biological
13. Nuclear
14. Ballistic Missile Defense
15. Personnel, Care, Protection and Survival
16. Human Performance
17. Counterinsurgency and Special Warfare
18. Environmental Analysis of Military Operations
19. Mapping
20. Construction Methods
21. Research for More than One of the Above
22. Research Associated with None of the Above
23. Testing
24. Management and Other Support

Categories 1 through 14 are called Hardware Categories, 15 through 20 are Non-Hardware Categories, and 21 through 24, Support Categories. This paper will use

the same classification scheme with the following modifications. Eliminate category 21 and assign its projects to the most valuable[8] system it supports. Remove category 23 and assign its projects to the category of the system it is designed to test. Eliminate category 22 and assign its projects to a new category called Basic Research. This category will have, in addition to those projects from the old category 22, all basic research projects which are not a part of some development plan. For example, there may be a basic research project in support of the development of MBT 70. This project would be assigned to category 3, Tank/Antitank. Another basic research project may be aimed toward category 3 but not part of some development plan. It would be assigned to the new category, Basic Research. Most projects that are called basic research or exploratory development would fall into this new Category 22. To summarize, the categories for this paper are:

Categories 1 through 20; no change.

Categories 21 through 24; eliminated and replaced by,
21 Management and Other Support
22 Basic Research

Now that a taxonomy has been defined, all that remains is to decide what belongs in each category. As was previously mentioned, the Army currently identifies each line item project as belonging to one of the categories. What is required for this model, however, is that systems be assigned rather than projects.

Although this idea has been previously introduced, this last sentence requires considerable expansion. Up to this point the terms "project" and "system" have been used more or less interchangeably. In most of the Systems Analysis literature on capital budgeting, a project refers to that entity which results in value. In the RDTE budget, a project is usually one of a group of contracts, all of which go

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[8] Most valuable will be explicitly defined later.

into the development program which hopefully results in an operational system. In this model it is the value of the system which we seek to measure, not the projects. To avoid this ambiguity a system will be defined as one or more RDTE line item projects or portions of projects which, when taken together, expect to result in value to the Army. Thus the Cheyenne system from category 1 might be defined as consisting of three projects; advanced development, test and evaluation, and operational systems development.[9] This discussion pertaining to the assignment of systems to categories applies only to categories 1 through 20. Categories 21 and 22 are treated differently than the others in the model.

One additional classification will be assigned to each system. The system will be further identified as belonging to one of three time periods depending on when, under reasonable funding levels, it can be expected to reach its operational readiness date (or, for Non-Hardware Categories, the objectives of the research will be reached).[10] The time periods are arbitrarily defined as:

T_1 : The five year period commencing with the fiscal year for which the budget is being formulated (hereafter called 1973).

T_2 : The five years following T_1

T_3 : The five year period following the end of T_2.

To summarize this classification scheme, with the exception of projects assigned to Categories 21 and 22, all other projects will be identified with a single system. Each system will in turn be assigned to a category and a time period.

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[9]The task of defining systems should be made easier by referring to the appropriate Development Concept Paper when one exists.

[10]A precise definition of how a system is time period classifi[illegible] deferred until Chapter 3.

D. MEASURING THE VALUE OF SYSTEMS WITHIN A CATEGORY

Having discussed the characteristics of value, we now turn to defining and measuring it. The value of an R & D system will be loosely defined as a notional (subjective) judgement made by an individual when he considers the capabilities of the system for meeting a specific need (or set of needs). Since this judgement is made in relation to the capabilities of other systems, it is often called relative value.

Many methods have been devised for measuring these subjective value judgements.[11] In general they vary widely in the ease with which they can be applied. One of the easiest to apply in terms of the time required is a "ranking-rating" method. Briefly, a survey respondent is first asked to ordinally rank the systems in order of importance. After this has been accomplished he is asked to assign a number between zero and ten to the value of each system, where ten represents the value of the system deemed most important. The assumption is then made that these numbers represent an interval scale of measurement of the relative values of the systems.[12] Due to the relative simplicity of this method, it will be the one described in this paper. However the model can be used with value parameters obtained from other methods, provided that they can be considered to be from an interval scale of measurement.

Assume for the moment that, contrary to reality, the value of each of the systems <u>within</u> a category[13] and time period has a single attribute and the attribute

[11] Burington [ref. 6] discusses the merits and shortcomings of some of the methods that have been applied in the R & D context. Fishburn [ref. 7] reviews 24 different measurement methods that have appeared in the OR and Economic literature.

[12] The implications of this assumption are discussed in Appendix A.

[13] The discussion of the value of systems within a category will exclude Category 21, Management and Support, and Category 22, Basic Research. These are treated separately in Chapter 4.

is definable in some unit of measure, W. It could then be said that the i^{th} system in the j^{th} category, a time period T system, has value during this period T of $V_{i,j}^{T} = y\,W$, where y is some non-negative real number. If this were an industrial model, W might be a dollar unit of measure and y the number of dollars, resulting in a value such as $V_{i,j}^{T} = 326$ dollars. The fact that such a real numbered value like 326 dollars cannot be measured for military R & D systems will be shown to be immaterial.

Suppose that a group of high-level DA planners, all experts in the systems of the j^{th} category, were surveyed and asked to ordinally rank the value of the time period T systems of the j^{th} category considering the following factors:

1. The performance characteristics of the resulting system will be exactly as specified in its current DCP.
2. The system's development costs are immaterial.
3. The system's operational readiness date will be as specified in the DCP.
4. The system's procurement and operating costs are a significant consideration.
5. The threats these systems may have to face are also a significant consideration.

Suppose further that, once an ordinal ranking was established, this same group of experts could respond to a second survey asking them to rate the value of each system on a scale of zero to ten, where the value of the most important system is taken to be ten. Assuming the response to this survey establishes an interval scale of value, we then have a measure of the value of the i^{th} system relative to the value of the q^{th} system, where the q^{th} system is the one deemed most important. Arbitrarily define this most important q^{th} system as the time period numeraire.[14]

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[14]The numeraire system is that system to which all the others are measured relative to; the denominator of the ratios.

We then have for each of the 20 categories and 3 time periods, a set of real numbers between zero and one;

$$\frac{V^T_{i,j}}{V^T_{q,j}} \quad \text{for} \quad \begin{array}{l} i = 1, \ldots, n_{j,T} \\ T = 1, 2, 3 \\ j = 1, \ldots, 20 \end{array}$$

where $n_{j,T}$ = the number of time period T systems in the j^{th} category. For example, for

j = 3	Tank/Antitank
T = 1	Systems which are first available during the time frame 73-77.
i = 2	Arbitrary assignment. Suppose it is "Antitank Gun Killer".
q = 1	MBT 70 (Assuming it was deemed most important)

Then

$$\frac{V^1_{2,3}}{V^1_{1,3}} = 0.9$$

would imply that the consensus of the subjective value judgement of the group of Tank/Antitank experts determined that the value of having Antitank Gun Killer during the time frame 1973-77 was only 90 percent of the value of having the MBT 70 tank.[15]

Once these parameters are established it is then desirable to get a measure of how the value of each system is degraded in time periods subsequent to the system's introduction into the inventory, considering the most likely technological obsolescence and enemy counter R & D moves. For example, the Tank/Antitank experts might respond with time degradation factors of $a^2_{1,3} = 0.66$ and $a^3_{1,3} = 0.1$, implying that the value the Army will achieve from MBT 70 during the time frame 1978-82 is only two-thirds what it was in 1973-77, and during 1983-87, only one-tenth of what it was in 1973-77.

[15] How a consensus measure is reached is discussed later.

One further set of data is required to make the value measurements <u>within</u> the j^{th} category commensurate. The systems within a category were partitioned into time periods to ease the problem of the survey respondents requirement to relate systems' values being developed for different time frames. However they now must be surveyed to relate the values of the most important systems from each period, the time period numeraires. Let the time period 1 numeraire be the denominator in these two measurements (now called the category numeraire) and measure the values of T_2 and T_3 numeraires relative to its value <u>in those time periods</u>. That is measure;

$$\frac{V^2_{q,j}}{a^2_{q,j}V^1_{q,j}} \quad \text{and} \quad \frac{V^3_{q,j}}{a^3_{q,j}V^1_{q,j}} \qquad \text{for } j = 1, \ldots, 20$$

The simple formula for relating the values of all systems <u>within</u> the j category relative to its category numeraire is then,

$$\frac{V^T_{i,j}}{V^1_{q,j}} = \frac{V^T_{i,j}}{V^T_{q,j}} \cdot \frac{V^T_{q,j}}{a^T_{q,j}V^1_{q,j}} \qquad \text{for} \quad \begin{array}{l} i = 1, \ldots, n_{j,T} \\ T = 1, 2, 3 \\ j = 1, \ldots, 20 \\ a^1_{q,j} = 1 \end{array} \tag{1}$$

Before continuing the development of the model it may be beneficial at this point to consider how such data might be obtained. One of the most widely researched techniques is the Delphi Method developed by Dalkey of the Rand Corporation [ref. 8]. It could be applied to this model in the following way. Write a carefully worded survey that included a precise list of the factors the respondents were to consider. Part of this list would be the performance characteristics and other information from the DCP of each of the systems in this category. Select at least ten respondents considered to be experts in the systems of this

category and issue them the survey individually.[16] Gather their responses and record how each of them rated the relative values and time degradation factors. Reissue the survey, but this time inclose the distribution of responses given for the last survey, and ask the respondents to reconsider their initial reply. Also ask that if they continue to rate a parameter outside the interquartile range of the group distribution of responses, to add a brief comment why they did so.[17] Reissue the survey again, inclosing the new distribution of responses and all the anonymous comments, and ask for a final consideration. Dalkey has shown in a number of tests of the Delphi Method that considerable convergence in responses occurs after as few as three iterations of this controlled feedback technique. Unfortunately there is no way of knowing whether or not it is converging to the "true" parameter, some measure of the relation of the intrinsic values of the systems.

Since the model will require a single measure to represent what is essentially a random variable parameter, this paper will consider the mean of the distribution of responses to be that measure, since in a statistical sense it represents the average of the responses. However, for the sensitivity analysis on the parameters discussed in Chapter 4, the end point of the interquartile range should also be recorded to provide the user with a feeling for the variance of opinion of his expert advisors.

E. COMMENSURABILITY BETWEEN CATEGORIES

The data collection effort outlined in the last section resulted in commensurate measures of value within each category, i.e., the value of the systems within the j^{th} category are measured on the interval scale of value of the category j numeraire

[16]In [ref. 8] Dalkey shows that the individual survey is preferred to a group meeting survey in that it eliminates a possible bias caused by one or more dominant personalities.

[17]The interquartile range is that interval containing the middle 50 percent of the responses

system. With this much information we could go on to Chapter 3 and continue the development of the model, but it would necessarily result in sub-optimization, since as yet there is no way of determining what the relative budget level for each category should be. Therefore it is now necessary to devise methods for translating the data developed thus far onto the value scale of a single RDTE program numeraire system. Arbitrarily define the category 1 numeraire as the program numeraire, and for simplicity of exposition, suppose it is the Cheyenne helicopter which has value $V_{q,1}$.[18]

Two methods, a primary and a secondary method, are discussed for making the value parameters of all systems commensurate. Each of them has various advantages and disadvantages which will be pointed out.

The primary method calls for surveying a group of high-level DA planners and asking them to rate the value of each of the category numeraire systems on the value scale of the program numeraire, Cheyenne (i.e., on a scale from zero to perhaps 20 where the value of Cheyenne, $V_{q,1}$, equals 10). This survey will result in a set of parameters reflecting a consensus measure (as previously discussed) of the value of each of the category numeraire systems relative to the value of the program numeraire, i.e.,

$$\frac{V_{q,j}}{V_{q,1}}.$$

The value of any system in the R & D program relative to the value of the program numeraire is then:

$$\frac{V_{i,j}}{V_{q,1}} = \frac{V_{i,j}}{V_{q,j}} \cdot \frac{V_{q,j}}{V_{q,1}} \qquad \text{for} \quad \begin{array}{l} i = 1, \ldots, n_j \\ j = 1, \ldots, 20 \end{array} \tag{2}$$

[18]The time period superscripts T will be dropped from here on since, after using equation 1, we have no further use for time period classifying the systems.

This method requires no mathematical assumptions, but presumes that each of the survey respondents are thoroughly familiar with the development programs of each of the category numeraire systems.

The secondary method requires the assumption that the value parameters determined for the systems within a category be additive, i.e.,

$$\frac{V_{i,j} + V_{k,j}}{V_{q,j}} = \frac{V_{ij}}{V_{qj}} + \frac{V_{kj}}{V_{qj}} .$$

This assumption means, for example, that if the values of systems i and K were rated at ½ the value of the category numeraire, then the value of having both the i and k systems is the same as the value of having the numeraire system.[19]

With the assumption of additivity of value the following simple equation can be formulated.

$$\sum_{i=1}^{nj} V_{i,j} \cdot V_j^* = N_j \qquad \text{for} \quad j = 1, \ldots, 20 \qquad (3)$$

where V_j^* represents the "slack value" for category j, and N_j is a measure of aggregated needs. In words Equation 3 says that the needs in this category equal the sum of the values of all the systems being developed, minus some slack value. While it is recognized that "needs" are really multi-dimensional, (i.e., in category 1 the Army has a need for both an attack helicopter and a surveillance helicopter) it is felt that the concept of aggregated needs is not an excessive abstraction since in the ASOP it is currently assigned a priority. V_j^* is included to cover two possibilities. First, due to technological uncertainty in the systems being developed, it is conceiveable that as a hedge against this uncertainty more systems are being developed than are expected to be required. In this case

[19]Further implications of this assumption, as well as methods for testing its validity, are discussed in Appendix A.

V_j^* would be a positive quantity. Alternatively, intelligence on a recent R & D breakthrough by a potential enemy may have suddenly increased N_j, and sufficient time has not yet passed to reach the concept formulation stage for one or more new systems. Here V_j^* would be a negative quantity. Obtaining a measure of V_j^* might be accomplished in the following way. Again using the Delphi technique, survey the category experts with questions similar to, "Assuming the development of all systems proceeds as in their DCP's, what system could be dropped from the program?" If the consensus were the k^{th} system, it would imply that

$$\frac{+V_j^*}{V_{q,j}} = \frac{V_{k,j}}{V_{q,j}} .$$

Alternatively, the consensus might be that no system can be dropped, implying that either the needs are exactly met or a gap between value and needs exists. The value of this negative slack might be determined by asking, "If in your opinion a system has to be added to the program to meet the needs in this category, to the value of which system currently in the program should the value of this new system be equal?" If the consensus were the l^{th} system, then

$$\frac{-V_j^*}{V_{q,j}} = \frac{V_{l,j}}{V_{q,j}} .$$

A very useful equation can result from taking the ratio of Equation 3 for two different categories, in particular category 1 and category j, and applying some algebraic manipulations.

$$\frac{\sum_i V_{i,1} - V_1^*}{\sum_i V_{i,j} - V_j^*} = \frac{N_1}{N_j} \tag{4a}$$

Multiplying both sides of this equation by the quantity

$$\frac{N_j}{N_1} \cdot \frac{V_{q,j}}{V_{q,1}}$$

yields

$$\frac{V_{q,j}}{V_{q,1}} = \frac{N_j}{N_1} \cdot \frac{V_{q,j}}{V_{q,1}} \left[\frac{\sum_i V_{i,1} - V_1^*}{\sum_i V_{i,j} - V_j^*} \right] \tag{4b}$$

and since

$$\frac{V_{q,j}}{V_{q,1}} = \frac{1/V_{q,1}}{1/V_{q,j}} ,$$

substituting for the second term on the right in Equation 4b we get

$$\frac{V_{q,j}}{V_{q,1}} = \frac{N_j}{N_1} \left[\frac{\sum_i \frac{V_{i,1}}{V_{q,1}} - \frac{V_1^*}{V_{q,1}}}{\sum_i \frac{V_{i,j}}{V_{q,j}} - \frac{V_j^*}{V_{q,j}}} \right] \tag{4}$$

Note that all the terms in the bracket in Equation 4 have already been determined. They are the values of the systems (or slack value) relative to their category numeriares. The term on the left, the value of the category j numeraire relative to the value of the program numeraire, is that quantity required for the use of equation 2. The term

$$\frac{N_j}{N_1} ,$$

however, is unknown. This represents the need during time period 1 for new category j systems relative to the need for Air Mobility systems. Determining these 19 parameters might also be done using the Delphi technique with a group of high level DA managers. As was mentioned, it is currently done in the ASOP

on an ordinal scale for the first 14 Hardware Categories. The extension that this secondary approach would require would be to ordinally rank all 20 categories, and then determine

$$\frac{N_j}{N_1}$$

in a manner similar to that used to find

$$\frac{V_{i,j}}{V_{q,j}} .$$

F. AN ALTERNATE APPROACH TO MEASURING VALUE

In developing a useful, working model, trade-offs must be made between how much information the model can provide the user in his decision problem and how much effort is required in data collection. The approach outlined thus far already requires a considerable data collection effort, and even more is asked for in the next chapter. It should be pointed out that the parameters required to be obtained by survey, are for the most part, the same as those needed for RAC's model, MEASURE I. This was purposely done to minimize the difference in the data collection effort. It should also be noted, however, that how the data are used to arrive at commensurate measures of relative value,

$$\frac{V_{i,j}}{V_{q,1}} ,$$

is considerably different for the two models. This point is discussed further in the next section.

Chapter 5 of this paper outlines a management information system that might be used to implement CARDBOMB. Mention is made that the user has the option to override any of the value parameters obtained thus far and insert his

own relative values; in essence, disagreeing with his advisors. However, the approach outlined in the last two sections gives him little insight into why the survey respondents replied as they did. The following approach might provide more insight, but at the cost of significantly increasing the data collection effort.

Recall that the value of a system and the need for it are both multi-attributed. The primary approach requires a survey respondent to consider a vector of performance characteristics as well as a vector of possible scenarios, weight the importance of each characteristic and the likelihood of each scenario, and aggregate all these factors in his head to arrive at a single measure of relative value. Hence a great deal of information is not available to a user of the model should he wish to consider altering the value parameters of one or more of the systems. Some of this insight might be regained by using the following alternate approach. Although it is outlined only for obtaining the relative values of systems within a category and time period, it could also apply to obtaining

$$\frac{V_{q,j}}{V_{q,1}} \quad \text{or} \quad \frac{N_j}{N_1}$$

(depending on which method, the primary or secondary, was used).

Survey the category j experts to obtain a list of what they consider the significant performance characteristics of the systems in the j^{th} category to be. Label these $k = 1, \ldots, m$. Follow this with a survey to determine the relative importance of each of these characteristics, relative, for example to $k = 1$. Label these weighting factors as b_k, where $b_1 = 1$. Again survey the category experts to determine the value of each of the systems relative to the value of the category numeraire for each of the characteristics. Label these

$$\frac{v_{i,k}}{v_{q,k}} \ .$$

With the additivity assumption it could then by hypothesized that the value of the i^{th} system was equal to the sum of its value in achieving each performance characteristic, weighted by the importance of the characteristic; i.e.,

$$V_{i,j} = \sum_{k=1}^{m} b_k \, v_{i,k}.$$

We would then have:

$$\frac{V_{i,j}}{V_{q,j}} = \frac{\sum_{k=1}^{m} b_k \frac{v_{i,k}}{v_{q,k}}}{\sum_{k=1}^{m} b_k \frac{v_{q,k}}{v_{q,k}}} \qquad (5)$$

$$= \frac{\sum_{k=1}^{m} b_k \frac{v_{i,k}}{v_{q,k}}}{\sum_{k=1}^{m} b_k} \qquad \text{for} \quad \begin{array}{l} i = 1, \ldots, n_{j,T} \\ j = 1, \ldots, 20 \end{array}$$

A simple example of this approach might help to clarify its use. Suppose the three surveys mentioned above for category 1, Air Mobility, resulted in the following set of data. Survey 1 determined that four important characteristics should be considered for Air Mobility systems.

k = 1	Air speed
k = 2	Maneuverability
k = 3	Weapons accuracy
k = 4	PEMA and OMA costs

Survey 2 determined that, considering the future needs for air mobility systems, the importance of each of these characteristics relative to air speed (determined to be most important) were

$b_1 = 1, \quad b_2 = 0.9, \quad b_3 = 0.8, \quad b_4 = 0.7$

Survey 3 resulted in the determination that the value of the design specifications and costs for system 2 relative to the value of those for system 1, the category numeraire were,

$$\frac{v_{2,1}}{v_{1,1}} = 0.5, \quad \frac{v_{2,2}}{v_{1,2}} = 1.2, \quad \frac{v_{2,3}}{v_{1,3}} = 0.8, \quad \frac{v_{2,4}}{v_{1,4}} = 1.3,$$

implying, for example that considering air speed alone, system 1 is twice as valuable as system 2. Using Equation 5 to aggregate this data we would have,

$$\frac{V_{2,1}}{V_{1,1}} = \frac{(1)\,(0.5) + (0.9)\,(1.2) + (0.8)\,(0.8) + (0.7)\,(1.3)}{1 + 0.9 + 0.8 + 0.7} = 0.9 \text{ (to the nearest tenth)}$$

Because of the additional data collection effort that would be required, this approach is considered by the author to be inappropriate for this model. Discussion of it has been included in this paper primarily to indicate a limitation to the approach discussed in the previous two sections the limitation of the lack of insight provided the user in understanding the factors that were considered in arriving at the relative value and relative category needs parameters. This limitation might be partly overcome by having the survey respondents submit a brief paragraph on why they decided on the responses they gave. These might be summarized in a short paper for each system and referred to by the user when he is considering whether or not he agrees with a particular parameter.

G. COMMENTS ON THE MEASUREMENT OF VALUE

Section B of this chapter outlined obstacles to the effective measurement of value for R & D systems. It should be apparent that the value measurement portion of this model has dealt with these problems in various ways. In this section each of these obstacles is recalled in order to provide the reader with more information on which to judge the validity of the methods used.

Lack of a unit of measure. Recall that it was assumed that a unit of measure, W, existed, and that the value of each system could be measured as having some real number, y, of these units. On an interval scale of measure, W cancels out of the equation

$$\frac{V_{i,j}}{V_{q,j}} = \frac{y_i\, W}{y_q\, W},$$

and the result is some dimensionless real number like 0.8. When a program numeraire (the denominator of all the ratios) is selected, it can then be said that the value of all the systems are measured on the value scale of this numeraire. For example

$$\frac{V_{i,j}}{V_{q,1}} = 0.8$$

is equivalent to $V_{i,j} = 0.8\, V_{q,1}$, implying that whatever real number is selected to represent $V_{q,1}$, $V_{i,j}$ must always be 0.8 of that number.

The subjective nature of value. In any analytical study there is a natural aversion to using subjective value judgements as important parameters. Nonetheless, very few decision problems exist where they are not required to be made. Regardless of the pains to which a decision maker may go to collect "objective facts" bearing on the problem, he ultimately must subjectively weigh these facts when faced with a tradeoff decision. This model assists him by presenting him with a consensus measure of the subjective value judgements of his advisors, but allowing him to override their advice and use his own judgements.

The aggregation of subjective value judgements. Regardless of the amount of objective information available to a group of experts, when they apply their own judgements it is unlikely that they will exactly agree. The Delphi Method for

aggregating their advice is used in this model because it represents the extent of the state of the art in what might be called "opinion technology." To keep the model reasonably simple, a single measure of value, the mean of their responses, is used. However the decision maker has the right, indeed the need, to know the extent of the disagreement of his advisors. Hence the end points of the interquartile range of their distribution of responses will be recorded as a measure of the variance of their opinion.

The non-commensurable nature of value. The model provides for partitioning the systems of the RDTE program, first into categories of systems which perform similar missions and then into time periods. After value judgements are made on these reasonably commensurate subsets, mathematically consistent methods are applied to relate the value of each system to the value scale of the program numeraire.[20] It was stated earlier that these mathematical methods are considerably different in this model and MEASURE I. RAC's model provides for the weighting of the relative value parameter within the j^{th} category by multiplying it by the relative need parameter of that category. In the notation of this paper this can be represented by

$$\frac{V_{i,j}}{V_{q,1}} = \frac{V_{i,j}}{V_{q,1}} \cdot \frac{N_j}{N_1} .$$

This produces a different result than that obtained by using Equations 2 and 4, as the following simple example demonstrates.

Assume a two category program with two systems per category where there exists absolute measures of value and need that are known with certainty as follows.

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[20]Besides identifying reasonably commensurate subsets, the pa ioning helps to eliminate bias. A proponent of Air Mobility does not rate the C enne relative to MBT 70.

Category 1 $\quad V_{1,1} = 20$

$V_{2,1} = 10$

$N_1 = 25$, implying $V_1^* = 20 + 10 - 25 = 5$

Category 2 $\quad V_{1,2} = 15$

$V_{2,2} = 10$

$N_2 = 20$, implying $V_2^* = 15 + 10 - 20 = 5$

Although it is apparent that

$$\frac{V_{2,2}}{V_{1,1}} = \frac{10}{20},$$

let us attempt to verify this using the methods of both models. Equation 4 results in;

$$\frac{V_{12}}{V_{11}} = \frac{20}{25}\left[\frac{\frac{20}{20}+\frac{10}{20}-\frac{5}{20}}{\frac{15}{15}+\frac{10}{15}-\frac{5}{15}}\right] = \frac{15}{20}$$

and using this in Equation 2 yields;

$$\frac{V_{22}}{V_{11}} = \frac{10}{15}\cdot\frac{15}{20} = \frac{10}{20}, \text{ in agreement with the data.}$$

The MEASURE I method would result in,

$$\frac{V_{22}}{V_{11}} = \frac{V_{22}}{V_{12}}\cdot\frac{N_2}{N_1} = \frac{10}{15}\cdot\frac{20}{25} = \frac{8}{15}, \text{ not in agreement with the data.}$$

This inconsistency is not the result of incorporating the concept of slack value. Even assuming V_1^* and V_2^* are zero, implying $N_1 = 30$ and $N_2 = 25$, the RAC method results in

$$\frac{V_{22}}{V_{11}} = \frac{10}{15} \cdot \frac{25}{30} = \frac{5}{9} \neq \frac{10}{20} \; .$$ [21]

<u>The multi-attributed nature of value.</u> This point was discussed at length in Section F where an alternate approach to measuring value was outlined. The principal approach requires the survey respondent to consider multiple attributes, but reduce them to a single measure of relative value. As mentioned, significant information may be lost to the user of the model when he desires to question the validity of a value parameter.

<u>Value as a function of time.</u> The model requires that the category experts estimate value degradation parameters reflecting the percent of the initial value remaining in time periods subsequent to the time period when the system is expected to be operational. Although five year time periods were defined, this is completely arbitrary.

<u>Scenario risk.</u> This becomes a factor for consideration by the survey respondents, and thus is not made visible in the model. The respondent must consider how the systems would perform in various circumstances, and then apply his own judgement concerning the likelihood of these scenarios. Thus, if all other factors were equal, if he considered a counterinsurgency war more likely than a major NATO encounter, the system designed for the former would have more value to him than one designed for the latter.

<u>Cost uncertainty.</u> Except as this factor might be considered by a survey respondent, this important consideration is not included in the model. This applies also to indirect objectives, e.g., effects on the R & D community, political,

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[21] This discussion is not to imply that this is the only difference in the value determination methods of the two models.

etc. Chapter 5 does outline, however, how sensitivity analysis can be conducted on cost parameters.

Technological uncertainty. Recall that the value determination surveys directed the respondent to assume that performance characteristics and operational readiness dates would be exactly as projected in the current DCP's. Thus value was measured independent of technological uncertainties. The next chapter introduces how the technological factors are considered.

The interdependence of systems' values. It would be unreasonable to require the Air Mobility experts to envision a future where the Army operated with only one system from this category. Therefore the value parameters have a certain degree of interdependence. Yet the mathematical formulation of the model will require that these values be assumed independent. This inconsistency has important implications concerning the solutions the model generates, particularly with regard to the usefulness of the model in providing insight into which systems might be dropped from the program. Discussion of these implications is deferred until Chapter 4.

III. RELATING VALUE TO COST

The development of the model has thus far dealt solely with methods for determining commensurate measures of value for the RDTE systems. The reader may have already formed an opinion concerning the usefulness and validity of those methods. Should the concepts developed in the previous chapter be rejected, the remainder of the model can still be useful, providing that; (1) some method is used to arrive at commensurate measures of value of the systems as currently planned, and (2) some measure of how that value changes over time is determined.

Recall that in the previous chapter, survey respondents were directed to disregard RDTE costs and technological uncertainty in determining the value parameters. We now turn to a consideration of these two factors in order to arrive at an intermediate goal — determining how the value a system is expected to achieve varies with RDTE dollar costs.

A. SOME CONSIDERATIONS ON COST

Costs are incurred in the implementation of the RDTE program for a number of resources, e.g., manpower, materiel, facilities and dollars. At some point in time any one of these resources might be a constraint on the program. However, since this is a budget model, it considers only the input of dollars. A still more restrictive definition of the costs considered must be used, however. To achieve the value determined in the last chapter, a system must be developed, produced and operated over its useful life. It would then appear obvious that the relevant cost considerations should be the total RDTE, PEMA and OMA cost ows,

appropriately discounted.[22] For models specifically pertaining to project selection, i.e., those dealing only with the decision of which systems should be in the program, all of these dollar costs must be considered. However, since this model is designed to investigate RDTE budget alternatives, only RDTE dollar costs are considered directly. Recall, though, that survey respondents were directed to consider PEMA and OMA costs in the determination of value.[23] To avoid ambiguity the term "cost" as used in the remainder of this paper will refer to the total RDTE dollar cost for a system unless otherwise specified.

B. EXPECTED VALUE OVER TIME FOR A FIXED BUDGET

What does an incremental change in the RDTE budget of a system buy in terms of value? Investigation of this question is an important step in determining how value varies with cost.

First, if the performance characteristics (and thus, probably the value) are upgraded, an increase in cost is likely to result. Similarly increasing the budget may allow the value to increase, either from an upgrade in the performance characteristics or a reduction in uncertainty that the characteristics, as planned, will be achieved.

A second way that value might vary with cost is in the time that is likely to be required in the development program before the system reaches operational readiness. An increase in the budget could possibly cause a shortening of the development time, while a reduction might require that the program be stretched.

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[22]While discounted costs are the appropriate consideration, discounting will be disregarded in the remainder of the text. It could be easily incorporated into the model.

[23]It is shown later that considering only RDTE costs, rather than total systems cost, will further restrict the use of this model in assisting with what might be called the ADD/DROP decision.

To determine how the value of each system varies with RDTE costs, it is necessary to gather more data from individuals intimately connected with the development of the system. To do this we might survey program managers with the following type questions.[24]

You are the program manager for System 127, Kickapoo helicopter. System 127 is composed of the following projects with a base case RDTE funding schedule as shown.

Project Number	Description	73	74	75	76	77	78	79	80
		FY Budget (in Millions)							
112	Platform Engr Dev	30	30	30					
163	Platform Adv Dev				50	50	50		
176	Engine Engr Dev	10	10						
193	Engine Adv Dev			10	10				
403	Wpn Sys Dev				20	20	20		
519	Test and Eval							5	
	Total Annual Cost:	40	40	40	80	70	70	5	
	Total RDTE Base Funding Cost: 345								

Question 1. What are the earliest, latest, and most likely operational readiness dates (ORD) at this base funding schedule?

Question 2. Consider a total RDTE Funding level ten percent greater than base. How would you recommend using these funds to change performance characteristics and/or ORD?[25] Record these new characteristics and the earliest, latest and most likely ORD. Also record the new funding schedule.

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[24] Each major hardware system has a program manager. For systems defined in Non-Hardware Categories, it is presumed that someone has the necessary familiarity to respond to such a survey.

[25] Note that the program manager is asked to give his opinion of what might be called the technically feasible and optimal trade-off of performance characteristics for ORD. It is presumed that his knowledge of the technological uncertainty leads to a feasible trade-off. Whether or not it is the "best" tradeoff is a matter to be carefully studied by users of the model.

Question 3. Answer question 2, but consider a total funding level 20 percent above base.[26]

Question 4. At what total RDTE funding level would the Army be better off dropping this development program?

Question 5. Letting Y be your answer to question 4, consider a funding level equal to Y + 1/3(345 - Y). Answer question 2 at this funding level.

Question 6. Consider a funding level of Y + 2/3(345 - Y). Answer question 2 with the total budget constrained at this level.

Note that question 4 identifies a "disaster funding level," at or below which the program manager feels the Army is better off dropping the system. The other questions are designed to collect information on value changes and readiness date changes for five funding levels above disaster, two on the high and two on the low side of the base case funding level.

Note also that for any of the four levels above disaster (excluding the base case) for which the program manager identified significant changes in performance characteristics, it would be necessary to treat the system as a new system and re-survey the category managers for different value parameters.

Determining the earliest, most likely and latest operational readiness dates is a technique from PERT theory used to construct a probability of completion distribution over time. The three parameters are usually used to construct a Beta probability distribution. For the purposes of this model, however, a simple linear cumulative distribution function will be defined as shown in Figure 1, where P(t) represents the probability that the system is in an operational readiness state in

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26The earliest ORD answer to this question defines to which time period the system belongs.

year t, and t_0, t_m and t_p represent the optimistic, most likely and pessimistic completion times.

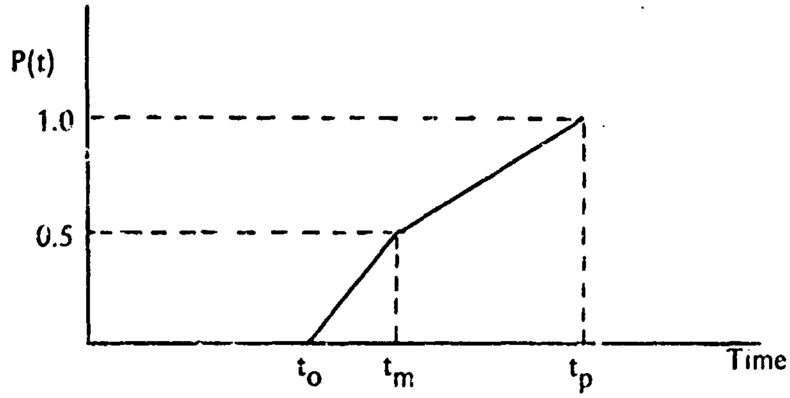

Figure 1. CUMULATIVE PROBABILITY OF OPERATIONAL READINESS OVER TIME

The one final set of data required for the model is indirectly a measure of its useful life. This data might be obtained by again surveying the category managers with a question like, "what is the earliest, most likely and latest years you would expect this system to be retired from the operational inventory?" Since it is possible that this probability distribution of retirement time is related to the operational readiness date (and therefore to the funding level), this question should probably be asked for each funding level and conditioned on the distribution of the operational readiness date for that level.

We now have reached the point where enough information is available to construct an expected value versus time curve for the i, jth system funded at level f, where:

f = 1	Funding level Y, "disaster funding"
f = 2	Y + 1/3 (Base - Y)
f = 3	Y + 2/3 (Base - Y)
f = 4	Base case funding
f = 5	Ten percent above base case
f = 6	Twenty percent above base case

Figure 2 shows the typical shape of the curve for a time period 1 system.

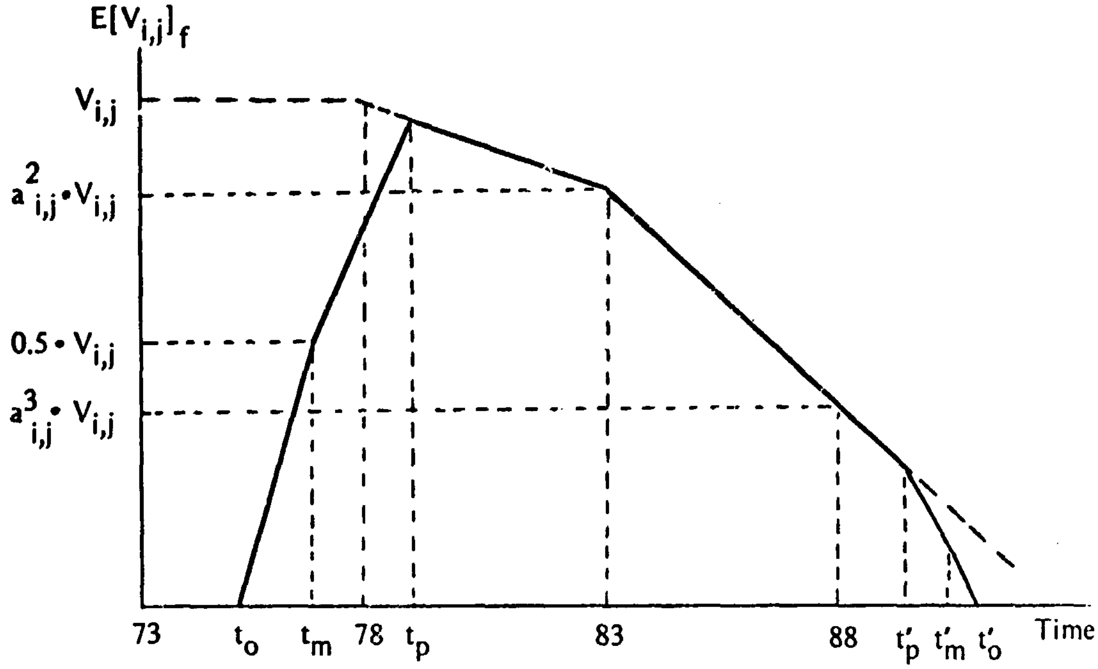

Figure 2. EXPECTED VALUE OF A SYSTEM OVER TIME FOR A FIXED FUNDING LEVEL "f"

In Figure 2, the highest curve, encompassing both dashed and solid line segments, represents the value of a system when availability is not considered. It is constructed using a linear interpolation between the value degradation points determined in the category managers' survey. The solid curve, the expected value of the system, is the product of the value of the system in year t times the probability the system is operational in year t.

For each system a curve similar to Figure 2 would be defined for <u>each</u> of funding levels 2 through 6. They may differ for each funding level in one of the following ways.

1. If the performance characteristics changed and resulted in a change in the value parameter for the system, the highest curve (value curve) will be shifted up or down.

2. Different distributions of the probability of entry and exit times will undoubtedly occur, causing a shift of the expected value curve in the uncertain region (the years where the probability of availability is less than 1) to the right or left.

C. THE TRANSFORMATION TO AN EXPECTED VALUE VERSUS COST CURVE

Since a curve similar to Figure 2 can be constructed for each system i for each of five different funding levels f, a method is available for plotting how the total life expected value varies with total RDTE funds. Define the total life expected value of the i^{th} system when funded at level f as follows:[27]

$$TV_{i,f} \equiv \sum_{t=73}^{t''} E\,[V_i]_f \tag{6}$$

where $t'' = \max\limits_{i} \left\{ t'_o \text{ (the optimistic retirement year)} \right\}$

For each system, apply Equation 6 for each of the five funding levels above disaster funding. A curve similar to Figure 3 will result.

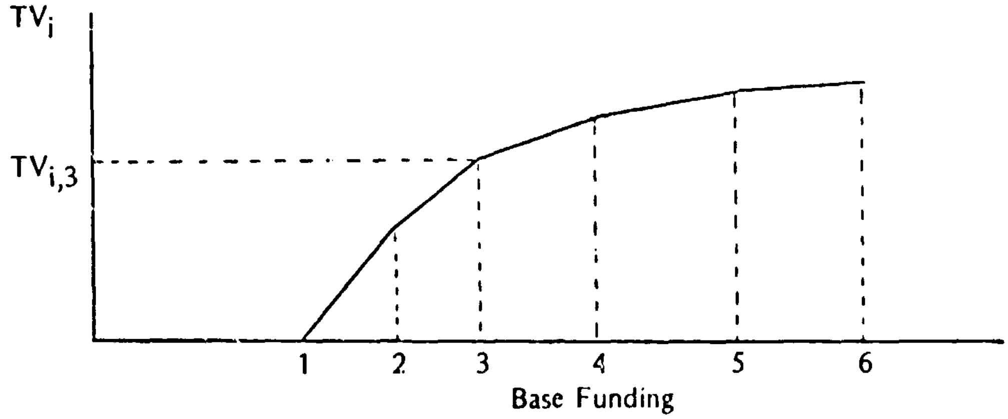

Figure 3. TOTAL LIFE EXPECTED VALUE VERSUS TOTAL RDTE COST CURVE

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[27] For simplicity of notation the category subscript j will be dropped. The second subscript f will be used to denote which of the 6 funding levels is being referred to.

An attempt might be made to fit an analytical curve between the data points, but it is doubtful that much would be gained, and it would result in a difficult problem to solve for an optimum.

Although Figure 3 shows total life expected value to be a simple function of total RDTE cost, actually it is quite complex. Incorporated in it is information concerning the system's value relative to all others in the program, its expected useful life, technological uncertainty and all the other factors that have been considered up to this point.[28]

Note might be taken of the shape of the curve. In the cost range [0, f = 6], or zero to 20 percent above base, it has a characteristic "S-shape", reflecting no value achieved until a certain "buy-in" cost is paid. In the cost range [f = 1, f = 6], value is shown to be an increasing function with cost, although increasing at a diminishing rate. The curve is said to be concave in the region [f = 1, f = 6]. Until such time as actual data is collected, there is no way of knowing for sure that such a curve will result for each of the systems. To assume that the curve is concave over the region of positive value is to accept the widely used assumption from economic theory of diminishing marginal returns. Simply stated this says that as funds are increased, a dollar buys more value, but not as much more as the dollar before it bought.

[28]Appendix A lists more precisely how all the variables are fu ctionally related to TV_i.

IV. FORMULATING MATHEMATICAL PROGRAMS FOR THE SIX DECISION PROBLEMS

Thus far the discussion has dealt primarily with defining the problem and gathering input data for the construction of total life expected value versus cost curves for each system in the program. In this chapter the discussion centers on how this information is used in mathematical programs to provide the decision maker with insight into selecting the "right" combination of the six options he has for altering the RDTE budget.

A. ALTERNATIVE TIME PREFERENCE STRATEGIES

Suppose international tensions had reached the state where it was increasingly apparent that World War III was likely to begin in the near future. Certainly the Army's R & D effort would emphasize concentration on near-term systems to the detriment of those planned for operational readiness much further in the future. Conversely, in a world situation where war seemed highly unlikely in the near future, the "best" strategy might be to concentrate the R & D effort on the later systems, gambling that the resources saved by a de-emphasis on near-term systems could be better spent on those being developed for the out years. Lacking certain knowledge of the future, there is no "best" strategy; nor should the analyst try to impose one. This is a strategy decision of great importance that should be made only at the highest levels.

Recall that a time period 1 system was selected as the category numeraire for each category, and that systems from later time periods were related to it using the time degraded value of the numeraire. In essence, then, all systems are measured

in what might be called present value. This was purposely done to allow for the input of alternative strategies. Loosely define three different strategies in the following manner.

Short range strategy: Relatively more emphasis is placed on achieving value in the near term.

Neutral strategy: The importance of achieving value is equal in all time periods.

Long range strategy: Relatively more emphasis is placed on achieving value in the out years.

Any of these strategies can be incorporated into the model in the following way. Ask the user to assign the number 1 to the time period he wishes to emphasize the most. Then assign fractional numbers to the other periods indicating their importance relative to the most important one. For example, parameters for a short range strategy might be (1, 3/4, 1/2), indicating that the user values operational systems twice as much in period 1 as in period 3. Similarly, parameters for a long range strategy might be (8/10, 9/10, 1), and for a neutral strategy (1, 1, 1).

Strategies can be incorporated into the model by using a time preference parameter, d_t, defined as shown in Figure 4 (for a short range strategy). Note that a constant rate of change of time preference is assumed, as well as a constant time preference for the years not between the data points. Once the user identifies the three parameters reflecting the strategy he wants to investigate, d_t is defined for each year t. The expected value curves are then modified to reflect the importance the user places on operational systems in any year by multiplying the expected value in year t times d_t. The result is what is commonly called discounted present value.

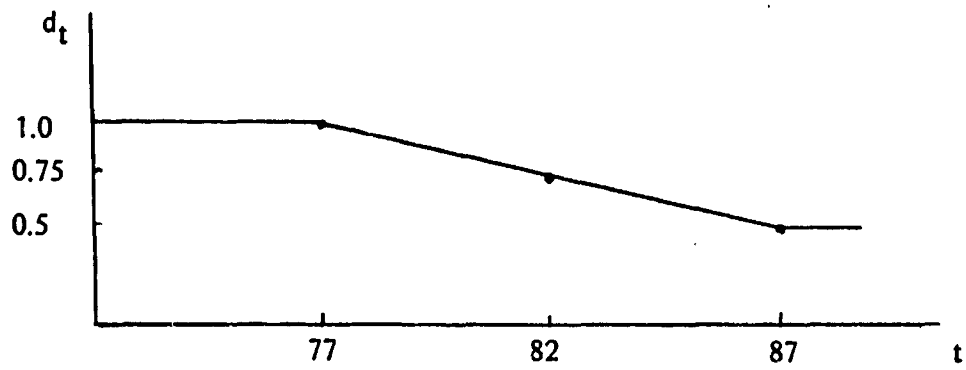

Figure 4. TIME PREFERENCE PARAMETER

The impact of inserting a time preference strategy can be seen in Figure 5. The solid curves represent the expected value as determined in the last chapter. They also represent a neutral (1, 1, 1) strategy. The dashed curves represent a short range (1, 3/4, 1/2) strategy, while the dotted curves are a (1/2, 3/4, 1) long range strategy. Naturally, since strategies alter the expected value curves, the total life expected value versus cost curves will also be changed.

Besides the obvious partiality for systems of a particular time period that results from selecting a strategy, strategies also cause changes in the relative importance of certain variables. For example, a short range strategy would lessen the advantage of a long life system, while a long range strategy lessens the importance of an earlier operational readiness date in a time period 1 system. All of these factors are incorporated into the model by the simple multiplication of $d_t \cdot E[V_i]_t$.

B. DETERMINING THE OPTIMAL PROGRAM FOR A GIVEN STRATEGY AND BUDGET

Once a strategy has been selected by the user, a specific TV_i versus cost curve is identified for each system. Suppose the user wishes to use CARDBOMB to determine an optimal RDTE program for a given total RDTE budget constraint

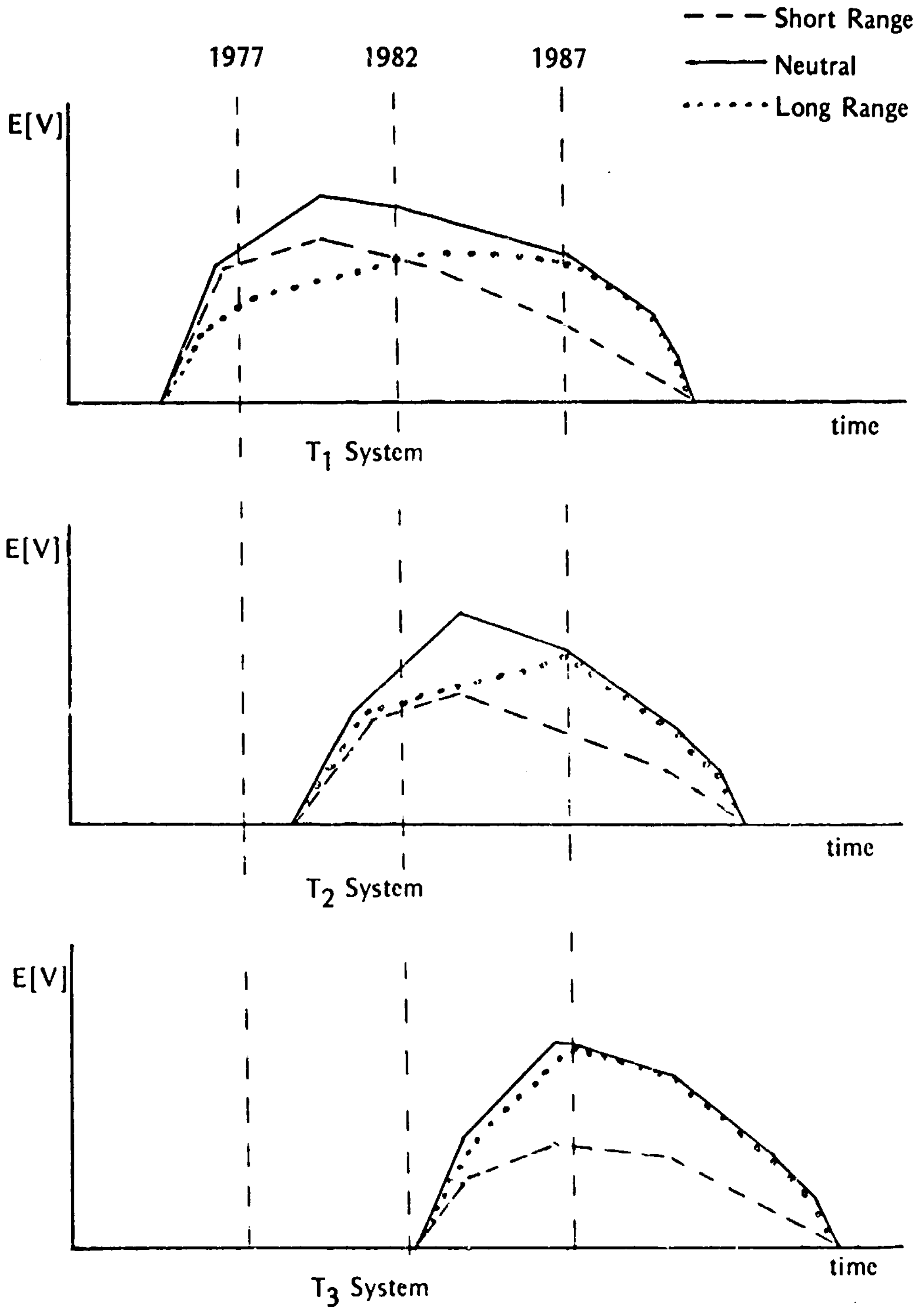

Figure 5. IMPACT OF ALTERNATIVE TIME STRATEGIES

for FY 73 of B billion dollars.[29] He desires that this be determined <u>without</u> considering dropping or slipping any of the systems currently in the base case program.[30] Since dropping a system is not to be considered, attention can be directed to the TV_i curves in the cost range above f = 1, the disaster funding level. That is, only funding levels 2 through 6 are to be considered feasible alternatives for each system. With the assumption that the values of the systems are independent of each other, the mathematical program can be formulated as follows:[31]

$$\text{Maximize:} \qquad \sum_{i=1}^{n} TV_i(x_i)$$

$$\text{Subject to:} \qquad \sum_{i=1}^{n} C_{i,f,73} \leq B_{73}$$

where x_i = the total RDTE cost of the i^{th} system

$C_{i,f,t}$ = the year t cost of the i^{th} system when funded at level f.

Unfortunately (in a mathematical sense) the budget constraint is on the FY 73 costs and not on the total RDTE costs. While it may be likely that the $TV_i(x_i)$ curves are concave, it is possible that some of the TV_i versus year t costs are not. As an illustration consider the two curves in Figure 6.

The right curve illustrates the case where year t costs as estimated by the program manager are higher at funding level 3 than they are at f = 4, certainly a possibility for some systems. Solving for an optimal solution when the curves

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[29]B billion would represent the total funds allocated to RDTE minus the amount required for the categories of Basic Research and Management and Support. These are still being excluded from the discussion. Although the first year is being used as the budget year under investigation, the model can also be used to investigate constraints in years other than this first year. Discussion of this point is deferred until Chapter 5.

[30]These two decision options are discussed in Sections D and .

[31]The implications of this assumption are discussed in Sectio of this chapter and in Appendix A.

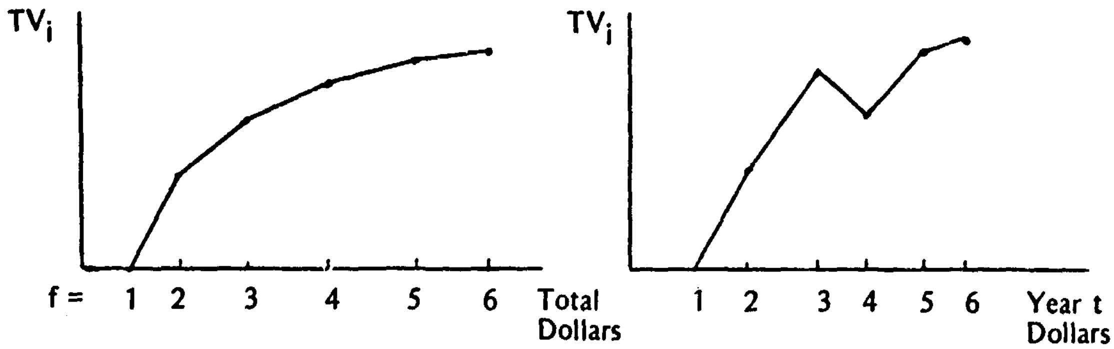


Figure 6.

in the objective function are not concave can be a difficult task involving complex search procedures. However the following simple algorithm (solution method) will lead to an approximation to the optimal solution.[32]

Algorithm 1

1. Calculate and label the slopes of the four linear segments of the TV_i versus total RDTE cost curve above funding level f = 2 as (i, s), for i = 1, . . . , n systems and s = 1, . . . , 4 slopes. These slopes are measures of marginal value between the funding levels.

2. Order these 4 n slopes in decreasing sequence, K = 1, . . . , 4n.

3. Calculate the initial value of a running sum

$$R_o = \sum_{i=1}^{n} C_{i,2,73} ;$$

the total FY 73 cost of the program when all systems are funded at f = 2. Set K = 1.

4. Identify the i^{th} system belonging to slope K. Calculate Q_K, the increase in FY 73 costs for this system when it is funded one level higher.
$Q_K = C_{i,f+1,73} - C_{i,f,73}$.

5. If $R_{K-1} + Q_K > B$, go to step 8.

6. If $R_{K-1} + Q_K \leq B$ set $R_K = R_{K-1} + Q_K$ and raise the funding level of the i^{th} system to f = f + 1.

7. Set K = K + 1 and return to Step 4.

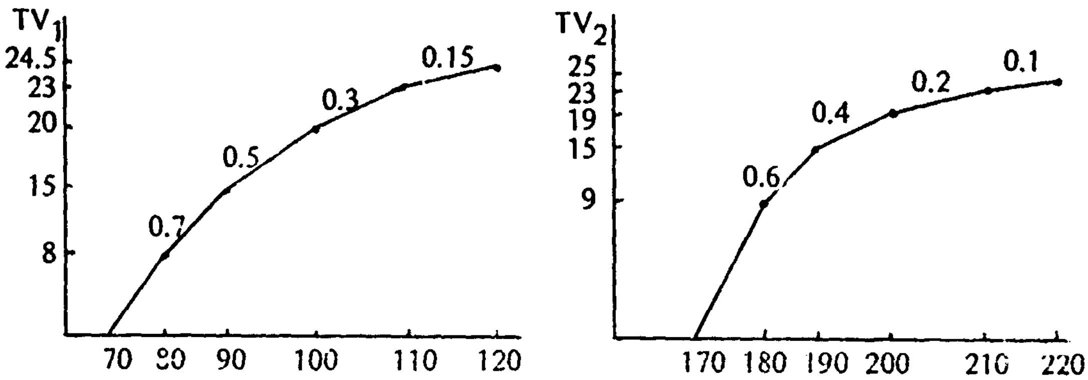
8. Stop. An approximation to the optimum has been reached.

[32]How close this approximation is to the optimum is discussed in Appendix A, as well as more elaborate procedures for finding the actual optimum.

A simple example of this algorithm may help to clarify its use. Suppose the RDTE program consisted of two systems whose total value versus cost curves were as shown below. Additionally, the program managers for these two systems had estimated the total FY 73 funding for each of funding levels 2 through 6 to be:

Funding Level

		2	3	4	5	6
System	1	25	30	35	40	45
	2	60	70	80	90	100



The slope ordering list called for in step 2 of the algorithm is reflected in the third column of the "Budget Incrementing Matrix" shown in Figure 7. Note $R_0 = 25 + 60 = 85$. If the budget constraint being investigated were $B = 115$, the algorithm would stop at $K = 4$, reflecting both systems funded at their base funding levels. The total value accruing to the program would be $20 + 19 = 39$.

	System	f	Marginal Value	FY 73 Funds Added	R
K = 1	1	3	0.7	30–25	90
2	2	3	0.6	70–60	100
3	1	4	0.5	35–30	105
4	2	4	0.4	80–70	115
5	1	5	0.3	40–35	120
6	2	5	0.2	90–80	130
7	1	6	0.15	45–40	135
8	2	6	0.1	100–90	145

Figure 7. BUDGET INCREMENTING MATRIX

As has been mentioned, once a strategy has been selected a TV_i versus cost curve is identified for each system. Additionally, a budget incrementing matrix is defined. If a user wished to investigate some alternative RDTE budget level for FY 73, the recommended changes from the base case are clearly visible in the Budget Incrementing Matrix. For example if he wished to investigate a constraint of B = 135, the model would recommend he consider raising system 1 to f = 6 and system 2 to f = 5.

Studying Figure 7 should make the need for the assumption of concave curves apparent. If at some point, diminishing marginal value was not the case for a particular system, then the slope sequence list might, for example, call for an increase to f = 5 before f = 4 was achieved. For systems that might exhibit a "violation" to the law of diminishing marginal value, the following procedure can be applied as a modification to Algorithm 1. Consider a system whole TV_i versus cost curve is as shown in Figure 8. For some reason little increase in value is

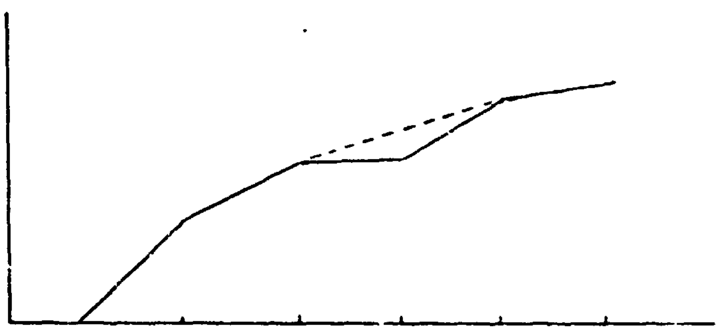


Figure 8. NON-CONCAVE VALUE CURVE

achieved in going from f = 3 to f = 4 (marginal value near zero). The dotted line between f = 3 and f = 5 does represent the marginal value between these points, however. The approximation to the optimal solution could be obt[illegible]d by using

the slope of this interpolated line in Algorithm 1. If it resulted in f = 2, 3 or 6 being recommended for this system, the non-concave portion of the curve had no impact. If f = 5 were selected, however, it would be necessary to check whether or not reducing this system to f = 4 would free funds to be spent on another system which would result in greater program value.

C. TESTING THE SOLUTION AGAINST THE BASE CASE PROGRAM

Suppose Algorithm 1 were used with an FY 73 budget constraint equal to that planned for the base case program. Undoubtedly a solution other than the base case would result, i.e., some systems would be funded higher than base funding (f = 4) and some would be lower. This could result from any of the following reasons.

1. The time preference paramete. used did not adequately reflect the actual time preferences of the collective leadership of DA.
2. Some of the value, need, useful life or other parameters, all consensus measures determined by advisors or program managers, do not reflect the views of the decision makers.
3. The base case program contains inefficiencies, i.e., after more careful analysis, a better program might result if funds were taken from some systems and given to others.
4. The approximation to the optimal solution determined by Alogrithm 1 was not close to opti...[1]
5. Some combination of two or more of the above reasons.

Resolving the differences between the solution as determined by the algorithm and the the actual base case program would be a difficult but useful exercise. First, it might identify inefficiencies in the actual base case, suggesting a better distribution of funds. Second, if the model is to be of any use at all in investigating alternative budget constraints, the parameters need to reflect a gene: l agreement

on their validity. An investigation of the divergence of the solution and the base case might take the following form.

First an attempt to resolve the time preference parameters to see if some particular set comes closest to producing a solution similar to the base case. For example, starting with a neutral strategy (1, 1, 1), move increasingly in the direction of a short range strategy.[33] The criteria for a set of strategy parameters being more suitable than another could be the number of systems funded at levels other than base funding. As an example, suppose this investigation resulted in the following.

Time Preference Parameters	Number of Systems Not at f = 4, Base Funding Level
(1, 1, 1)	25
(1, .95, .9)	20
(1, .9, .85)	15
(1, .85, .80)	5
(1, .8, .7)	10
(1, .7, .6)	20

It might then be assumed that (1, 0.85, 0.8) most closely reflect the time preference of DA decision makers. Of course there is no way to prove that these parameters are "correct", but they do imply that DA decision makers have acted as if these were their time preferences.

The investigation might then continue with a careful analysis of the systems not at funding level 4. This investigation might result in agreement that the responses to the surveys were unrealistic in some cases and some of the input parameters need adjusting. Alternatively it might be agreed that the base case would indeed be better if some redistribution of funds were made.

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[33]Due to the nature of national defense, defense decision makers are generally presumed to prefer forces in being to systems planned for further in the future. Starting the investigation from a neutral strategy and moving toward strategies which are more and more short range should minimize the number of sets of parameters required for this investigation.

D. IDENTIFYING SYSTEMS TO BE SLIPPED

The last two sections dealt with the problem of determining an optimal RDTE program for a given fiscal year budget constraint. The method formulated assumed that the user did not wish to consider slipping a system's development schedule one or more years. As has been stated, slipping consists of delaying the start of a development program, or interrupting one that has already begun (such as between the engineering development and advanced development stages with the intent of starting it up again at a later date). This, of course, is a decision option open to the Army for altering the RDTE budget program for any given year. We now consider how the model can assist the user in identifying systems which might be slipped one or more years.

The first consideration that must be addressed is which systems might reasonably be considered for slipping. Certainly if one or more of the projects of a system scheduled for FY 73 are "carry-overs" from FY 72, it might be unreasonable to expect that it would be economical to interrupt work on those projects for one or more years and then begin them again. This fact alone will undoubtedly eliminate many systems from consideration for slipping.

One must also consider what might be gained or lost from slipping the schedules of systems. The first "gain" might be called a reduction in technological uncertainty. The development cycles of systems follow a general sequential pattern starting with the concept development stage and progressing through engineering development, advanced development, test and evaluation, and finally, production and operational systems development. Between each of these stages of development a detailed review of the progress that has been achieved must be made and a decision issued on whether or not to begin the next stage. It might be determined

that, in order to overcome technical problems which have not been resolved, the best course of action is to slip the next stage one or more years. The decision problem associated with slipping a system's development schedule to overcome technical difficulties is not addressed in this model. It is assumed that these decisions have already been made in arriving at the base case program.

Besides reducing technological uncertainty, the Army might also wish to consider slipping the development schedule of one or more systems to save funds in a particular year. The model can assist with this decision option by identifying a measure of the value lost per dollar saved when a system is slipped.

Suppose that for a particular time strategy and total budget constraint, Algorithm 1 resulted in funding level f being optimal for the i^{th} system. The expected value versus time curve for this system at this funding level might be as shown by the solid line in Figure 9. Under the assumptions that (1) distribution of

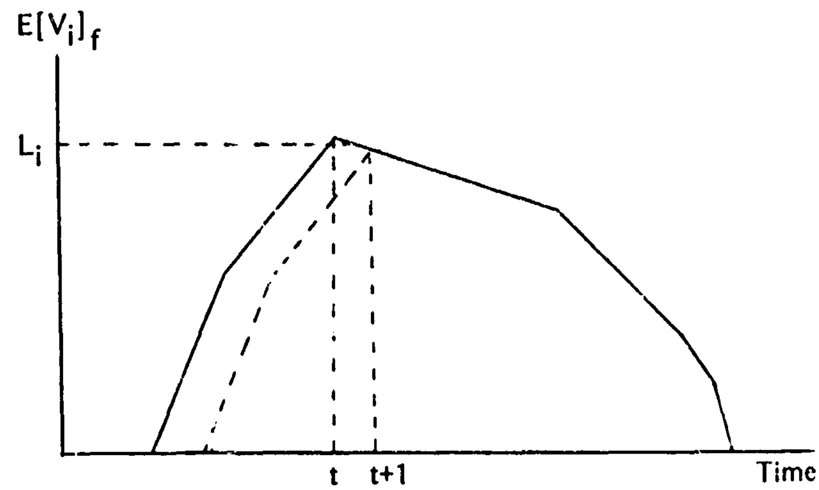

Figure 9. LOSS IN VALUE, L_i, CAUSED BY A ONE YEAR SLIP

the probability that a system is operational by year t is affected by a one-year schedule slip only to the extent that it is displaced one year, and (2) the probability

distribution of the system retirement date is not affected by a one-year slip,[34] then the loss in value, L_i, caused by a one-year slip to the development schedule of the i^{th} system can be approximated by;

$$L_i = \frac{E[V]_{i,t} + E[V]_{i,t+1}}{2} \tag{7}$$

Dividing L_i by the FY 73 budget for the i^{th} system $C_{i,f,73}$, would then determine an approximation to the loss in value per dollar saved by a one-year slip. This presumes that no money would be required to keep the program "alive" during the slip. If this were not the case, $C_{i,f,73}$ would represent the difference.

If a user of the model wished to consider slipping as an alternative for investigating different RDTE programs, this could be incorporated in the following way.

Algorithm 2

1. Use Algorithm 1 to determine the approximation to the optimal RDTE funding level f for each system when slipping is not considered.

2. For the subset of systems identified as candidates for slipping, calculate

$$S_i = \frac{L_i}{C_{i,f,73}}$$

the loss in value per FY 73 dollar saved.

3. Order the set of $\{S_i\}_k$ in increasing sequence $k = 1, \ldots, n$. (The system with the smallest loss in value per dollar saved is first in this sequence, $k = 1$). Set $k = 1$.

4. Identify the k^{th} system as the next system in the budget incrementing matrix to be increased if more FY 73 funds were available. Calculate

[34] An alternative to these assumptions would be to gather more data on how a one year slip would affect the earliest, latest, and most likely operational readiness dates and system retirement dates.

$$G_k = \frac{TV_{k,f+1} - TV_{k,f}}{C_{k,f+1,73} - C_{k,f,73}}$$

the gain in total value to the k^{th} system per FY 73 dollar added.

5. If $S_{i,k} \geq G_k$ (if the loss in total value caused by slipping system i one year is greater than the gain in total value to system k when the money saved by the slip is transfered to system k), go to step 8.

6. If $S_{i,k} < G_k$, slip system i one year and transfer the savings to system k.

7. Let $k = k + 1$ and return to Step 4.

8. Stop. Slipping any more systems and transferring the funds to other systems will only cause a net decrease in the total value of the RDTE program.

E. IDENTIFYING WHICH SYSTEMS MIGHT BE DROPPED

Another alternative for altering the RDTE program is to drop one or more systems. As has been mentioned, this decision problem is normally addressed on a system by system basis during the extensive progr[illegible]s review following completion of a stage of the development cycle, or when some threshold parameter of the DCP has been violated. It could also be addressed on a total program basis, i.e., given a particular FY 73 budget constraint, would more total value accrue to the RDTE program if one or more systems were dropped and the savings transferred to other systems? It has previously been stated that CARDBOMB can only indirectly assist in this decision problem for reasons which can be summarized as follows.

The interdependence of the value parameters. As has been mentioned, the relative value of the i^{th} system is a consensus measure of a group of experts who were not asked to envision a future where the i^{th} system was the only one in the inventory. In other words, the value of this system depends on the value which results in other systems. The optimization procedure discussed thu[illegible]r has ignored this interdependence and assumed that the value achieved by one system does not

alter the value of another. This independence of value assumption says, for example, that the change in expected operational readiness date and performance characteristics caused by a change in the funding level of the i^{th} system in no way affects the value of other systems. For changes in value in the region around the base case funding level, i.e., plus or minus 20 percent of base funding, this assumption is probably not a bad approximation for most systems. This situation will undoubtedly not be the case when dropping a system is considered. While moving up the operational readiness date of Tank System A one year probably does not significantly affect the value of Tank System B, dropping System A would undoubtedly have a significant impact on the value of System B. Models have been developed which take into consideration the interdependence of value.[35] In general they would require a far greater data collection effort and complex dynamic programming solution methods.

The interdependence of value and total system's cost. The surveys to determine the value parameters asked the respondents to consider PEMA and OMA costs in arriving at a measure of a system's value. If all other considerations were equal, a system with high PEMA and OMA costs would be rated lower than a cheaper system. This technique was used to insure that these important cost considerations were included in the model, but not on the cost axis of the TV_i versus cost curves, since the model is designed primarily for investigating only the RDTE budget. In addressing the problem of which, if any, systems could be dropped, the appropriate measure would be the total value (measured independent of all cost) per total system's cost dollar.

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[35] See Weingartner [ref. 9] for a survey of these models.

Keeping in mind these considerations, CARDBOMB still might provide insight into the decision problem of which systems might be dropped. Using the total life expected value for the i^{th} system determined using algorithms 1 and 2, divide this by the total expected system's cost. That is, for each system i, calculate

$$D_i = \frac{TV_i^0}{x_i + y_i + \sum_t p_t z_i}$$

where

TV_i^0 = total life expected value at the optimal funding level.

x_i = total RDTE cost at the optimal funding level

y_i = total PEMA cost.

z_i = annual OMA cost.

p_t = as before, the probability the system is operational in year t.

Ordering the set of D_i in increasing sequence, while certainly not establishing a priority list for dropping systems, could assist the Army by focusing attention on which development programs might be more carefully analyzed. The first system in the list would be the one with the lowest average value, or value per total dollar.

F. ANALYZING THE IMPACT ON THE TOTAL PROGRAM OF ADDING A NEW SYSTEM

By the time a new system has finished the concept development stage, considerable cost-effectiveness analysis has been conducted on alternative approaches to meeting the threat for which it is designed. Besides these analyses a necessary input to the DCP is the impact the introduction of this system will have on other Army programs, i.e., what must be given up to get it.

As was the case in the question of which systems might be dropped, CARDBOMB is limited in assisting with this problem for much the same reasons — the interdependence of the value parameters and the treatment of PEMA and OMA costs as negative value rather than independent variables. However insight to this problem still might be gained in the following way.

As was done for systems already in the program, survey category managers to determine

$$\frac{V_i}{V_q^{\,1}} ,$$

a measure of the value of this new i^{th} system on the same scale as all the other systems.[36] Similarly, gather data for four alternative funding levels to arrive at a TV_i versus RDTE cost curve. Include this new curve in the program and, using Algorithm 2 and the same total budget constraint, solve for an optimal solution. This new solution will determine two things. First, it will recommend at which of the five funding levels this system ought to be developed, and second, the impact on the systems whose funding levels had to be lowered determine a measure of what must be sacrificed in the RDTE program to get this system. That is, introducing System Z into the program might require reducing the design characteristics of System Y and stretching the operational readiness date of System W one year. Alternatively, the Army might decide to maintain the design characteristics of System Y, raise the RDTE budget constraint and make up the difference in some other budget program. In any event CARDBOMB has assisted by identifying in terms other than dollars, what must be given up to get System Z.

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[36]A way of avoiding the interdependence of value problem in [illegible]s case is to survey to determine new relative value parameters for all the system[illegible] in this category when the new system is considered part of this category.

Of course these measures of what must be given up only consider the RDTE budget. Lacking an optimization model which encompasses the RDTE, PEMA and OMA budgets, we must resort to the average value methods of the previous section. Therefore, besides conducting the analysis just discussed, it might also be appropriate to determine where the D_i for this system, the total value per total systems dollar, fits into the sequence of D_i discussed in the previous section. If it turned out to be high on the list, meaning it has one of the lower average values in the program, this could imply that it might not be worth the cost and should be studied further.

G. BUDGETING PROJECTS WHICH ARE NOT COMPONENTS OF A SYSTEM DEVELOPMENT PLAN

The discussion of the model has thus far ignored projects which are not related to a specific system's development plan. In the classification scheme of this paper, these projects fall into Category 22, Basic Research, and Category 21, Management and Support. We now turn our attention to these two categories.

The inputs required for an optimization model must answer two important questions; what is the value of the system, and how does this value vary with cost. Undoubtedly by the end of Chapter 3 the reader had developed an appreciation for the difficulty in providing quantitative answers to these questions. The problem is even more difficult when considering basic research and exploratory development projects. Consider a hypothetical project designed for investigating military applications of a rotary engine. Unlike a system with a development plan which identifies expected performance characteristics, the threat it is designed to meet and other factors, just what might result from this project is highly uncertain. Equally uncertain is how a funding change will affect the results of the project. For these

reasons the model will treat category 22 projects differently than it has treated systems.[37]

Define twenty sub-categories of category 22 to correspond with the classification scheme for systems, i.e., sub-category 1 would be basic research projects associated with Air Mobility. Further define sub-category 21, Pure Research, consisting of all projects (excluding Management and Support) not otherwise classified. Using the methods of Chapter 2 for determining value parameters of systems, obtain a parameter for each of the Category 22 projects. That is, for each of the projects within the j^{th} sub-category, obtain a consensus measure,

$$\frac{V_{ij}}{V_{qj}},$$

of the relative value of what is <u>expected</u> to result from the projects. Then use these with either the primary or secondary methods of Chapter 2 for determining the value of any sub-category project relative to the value of the Category 22 numeraire,

$$\frac{V_{ij}}{V_{q1}}.$$

Ideally we would now like to know how this value varies with funds so that measures of marginal value could be obtained. Unfortunately basic research projects do not lend themselves to this measurement as well as system do. While an increase in funds might result in completing the project sooner, in general this advantage would be impossible to measure in terms of changes in value. However, under the assumption that for small funding changes near base case funding, the ratio of the

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[37]For a more detailed discussion of considerations pertinent to modeling basic research, see Quinn [ref. 10].

marginal values of two projects are directly proportional to the ratio of their average values, we can develop a method for investigating alternative basic research budgets.

We must first determine a method for measuring the value of the i^{th} project[38] per total RDTE dollar, x_i being spent on it, defined as

$$A_i = \frac{V_i}{x_i}$$

the average value. Recall that on an interval scale of measurement, the particular value assigned to the numeraire has no significance. Arbitrarily let $V_q = x_q$. We then have

$$A_i = \frac{V_i}{x_i} = \frac{V_i}{V_q} \cdot \frac{V_q}{x_i} = \frac{V_i}{V_q} \cdot \frac{x_q}{x_i} \tag{9}$$

Note that on this arbitrarily selected scale, the value per dollar, or average value, for the numeraire project reduces to $A_q = 1$. Another project which had only half the value of the numeraire but was only one-tenth as expensive would have $A_i = 5$.

Before turning to the development of a decision rule, let us examine the implications of the assumption stated above. Figure 10 shows two basic research

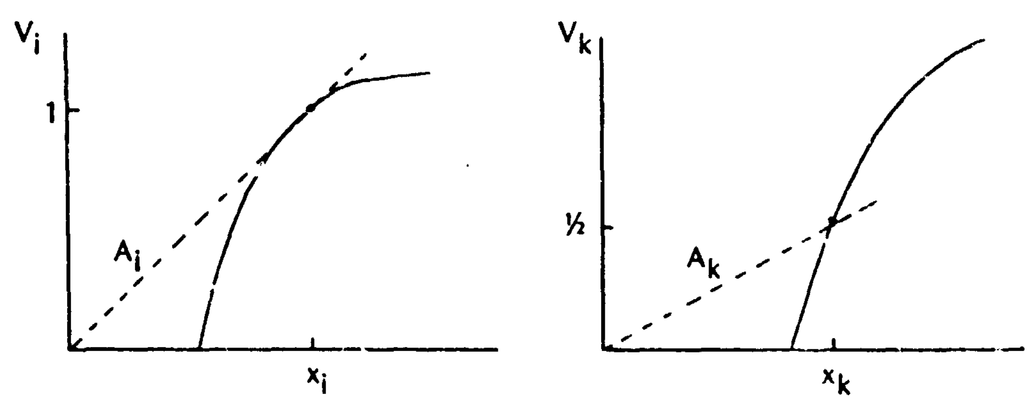

Figure 10. IMPLICATIONS OF THE AVERAGE VALUE ASSUMPTION

[38]The sub-category subscripts j are now dropped for simplicity of notation.

projects each funded at a total RDTE cost of $x_i = x_k$. Their values at this base funding were measured at 1 and ½ respectively. Their average values, or value per dollar, are then measured as the slope of the dashed line from the origin. The solid curves are hypothetical value curves which, as has been mentioned, are not known. Since they are unknown, so is the marginal value at this funding level. If they were known we would want to increase the one with the greatest marginal value (or decrease the one with the smallest). Figure 10 shows that adding a dollar to the budget of project k would cause a greater increase in value than adding it to i, even though project i has the greater average value. This discussion is added to demonstrate how easily the assumption can be violated; the ratio of average values are not always proportional to the ratio of marginal values. However, lacking information on the curve itself, it might be further assumed that the base case funding is near the point where value is "falling off", as is the case in the left figure. In other words the project has reached the point where hiring a few more scientists just isn't going to add that much. With this further assumption, we not continue with an algorithm for altering the Category 22 budget.

We wish to insure that if the budget gets increased, the projects with higher average values receive proportionally more of the increase than those with lower average values. Conversely, if the budget is reduced, the lowest average value projects get reduced the most. These "decision rules" are depicted in Figures 11 and 12, where

$$A' = \max_i A_i \qquad \text{and} \qquad A'' = \min_i A_i \quad .$$

Suppose a user of the model wishes to investigate the Category 22 budget program that would result from using this method for a total constraint of D million

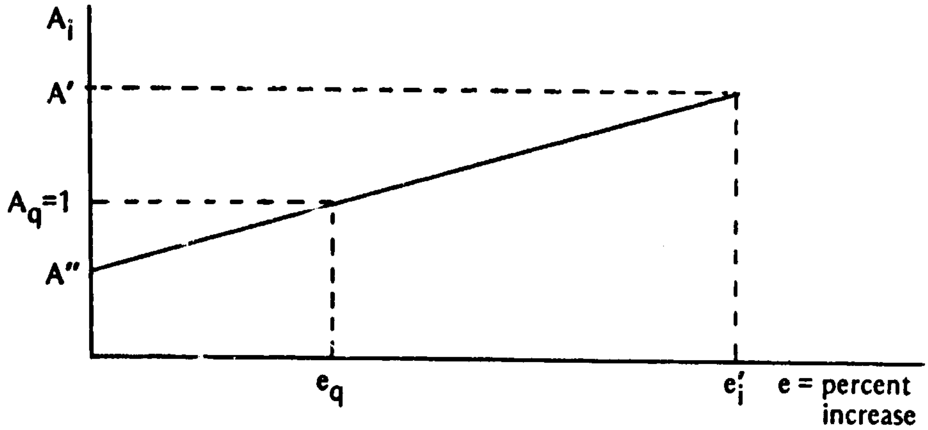

Figure 11. COMPUTING A PERCENTAGE INCREASE FOR BASIC RESEARCH PROJECTS

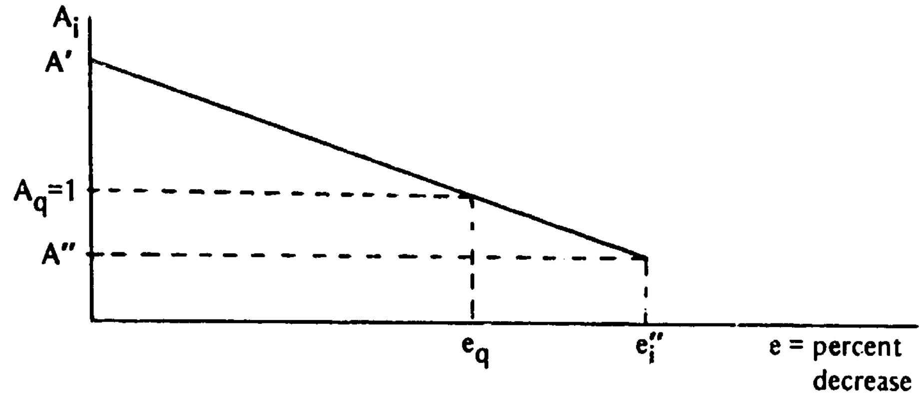

Figure 12. COMPUTING A PERCENTAGE DECREASE FOR BASIC RESEARCH PROJECTS

dollars, less than the base case program total constraint of E million. The following formula calculates the percentage reduction to each project that will be required to meet this new constraint.

$$e_i = \frac{(A' - A_i)\,(E - D)}{\sum_i (A' - A_i)\, C_{i,4,73}} \tag{10}$$

To illustrate the use of this formula, consider a three project basic research program with average value and FY 73 base funding costs as follows.

$A_1 = A' = 5$ $\qquad\qquad$ $C_1 = 10$

$A_2 = 3$ $\qquad\qquad$ $C_2 = 20$

$A_3 = A'' = 1$ $\qquad\qquad$ $C_3 = 40$

Note that the total base case funding, E = 10 + 20 + 40 = 70. Suppose the user wished to investigate a constraint of D = 60. Equation 10 would result in the required percentage reduction for each project as shown.

$$e_1 = \frac{(5\text{-}5)\ (70\text{-}60)}{(5\text{-}5)\ (10) + (5-3)\ (20) + (5\text{-}1)\ (40)} = \frac{0}{200} = 0$$

$$e_2 = \frac{(5\text{-}3)\ (70\text{-}60)}{200} = \frac{1}{10} = 10 \text{ percent}$$

$$e_3 = \frac{(5\text{-}1)\ (70\text{-}60)}{200} = \frac{1}{5} = 20 \text{ percent}$$

Indeed, $10 + \frac{9}{10} \cdot (20) + \frac{8}{10} \cdot (40) = 60$, and the new constraint is met.

Equation 11 is a similar formula for computing percentage increases from base funding.

$$e_i = \frac{(A_i - A'')\ (D - E)}{\sum_i (A_i - A'')\ C_{i,4,\ 73}} \tag{11}$$

It should be apparent that no optimization is involved in this method for altering the budgets of Category 22 projects. What is reflected in the solution, however, is that projects with high value per total dollar figures are increased proportionally more and decreased less when the total Basic Research budget is altered. Of course

the resulting solution would have to be carefully investigated to insure that the changes could be absorbed.

To summarize, the decision rule for altering the budgets of individual Category 22 projects is: If the budget constraint for Category 22 projects is greater (less) that the base case constraint by an amount D - E (E - D), then increase (decrease) each project the percentage of its base case funding as determined by Equation 11 (Equation 10).

Studying changes to the budgets of projects in Category 21, Management and Support, is not included in this paper. In the management information system outlined in the next chapter the user can change the total for this category, but no method is developed here for investigating what changes might be considered for each project. These changes would undoubtedly be made after a careful investigation of the organizational slack (fat) in each of the headquarters elements.

H. INVESTIGATING THE BUDGET LEVEL OF THE RDTE PROGRAM

A characterization of an optimal solution for a given budget constraint (i.e., an optimal mix of systems' budgets within the RDTE program) is that there is no other way that the funds can be distributed such that more total value will accrue to the program. This optimal (or efficient) mix implies nothing about what the optimal level, or total RDTE budget constraint should be. In this section a method is developed for investigating this question.

Suppose that over the past several years, the RDTE budget has averaged about nine percent of the total Army budget and that under current DOD fiscal guidance, this nine percent represents 1.7 billion dollars. Suppose further that it has tentatively been decided to fund Categories 21 and 22 at 0.7 billion. The question is then,

should the remaining budget for systems be one billion, a little more or a little less? Insight into this question might be gained in the following way.

Using Algorithm 2, find the approximation to the program of optimal mix for RDTE budget constraints ranging from 0.9 billion to 1.1 billion, in increments of 10 million. For each of these 20 budget constraints, calculate

$$\sum_{i=1}^{n} TV_i$$

when each of the n systems are funded at optimality. Plotting these against the 20 budget constraint points might lead to a curve similar to Figure 13. If such a

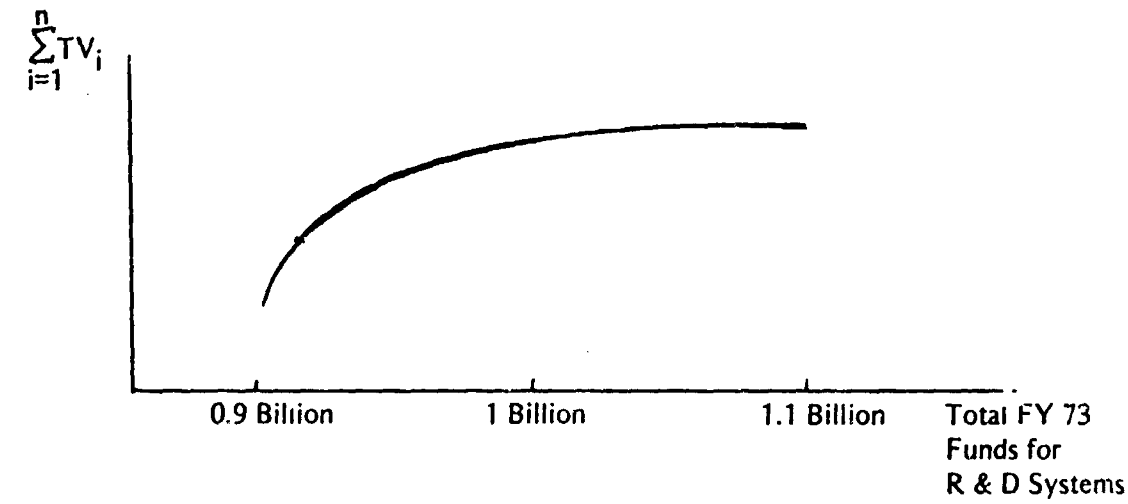

Figure 13. TOTAL PROGRAM VALUE VERSUS TOTAL COST CURVE

curve were to result, the implication is that increasing the budget from 0.9 to 1 billion significantly increases the total program value, while a relatively smaller increase is achieved when going from 1 to 1.1 billion.

It is impossible to predict without data what the shape of this curve might be. It will be non-decreasing, however, since it results from the addition of systems' value curves which are non-decreasing. Whatever its exact shape turns out to be will determine how much insight into the problem this exercise might provide.

For example, if a generally linear curve were to result, or one where no discernable change in the rate of increase was apparent, relatively little insight would be provided in comparison with that implied by the Figure 13 curve. In fact a linear curve would provide no guidance in selecting a "proper" budget level, since it reflects no decrease at all in the rate at which total program value increases as funds are increased.

V. IMPLEMENTING THE MODEL AS A MANAGEMENT INFORMATION SYSTEM

Although the solution algorithms for this model are relatively simple, they require a great deal of data manipulation. The repetitious nature of these calculations lend themselves to computerization, and the model itself to a computer assisted management information system (MIS). In this chapter an MIS which could implement CARDBOMB is outlined; one which seems to be suitable for incorporation into the DEAN MACHINE system. The specific desires of the principal users would undoubtedly result in an MIS quite different than the one proposed here. This chapter is designed more to point out the potential uses of the model in assisting with the RDTE budget planning problem, and the relative simplicity of the computer programs required. It might also prove to be a useful starting point in the development of a working MIS.

A. THE BACK-UP SEGMENT OF THE MANAGEMENT INFORMATION SYSTEM

Unlike pure costing models which, over time, tend to become "believeable" to users when their time saving capabilities and accuracy have been demonstrated, an optimization model of this type which incorporates many factors of a subjective nature and manipulates them in an almost "magical" fashion has to be clearly understood to be useful. The amount of insight into a decision problem that a particular solution might provide is directly proportional to how well the user understands the model.[39] Consequently an MIS must consist of more than just a

[39] For a discussion of some of the pitfalls of designing an MIS, see Ackoff [ref. 11].

method for allowing a user to interface with a computer. A users' manual which clearly states the assumptions, approximations, methods, capabilities and limitations of the model is an integral part of the MIS. Equally important is a document to which the user can refer when studying the parameters of systems he might wish to check while investigating a specific solution the model recommends. Although OCRD produces a Project Listing of the Program 6 base case, it is organized in the format of the budget and recognizing which projects belong to which systems is sometimes a difficult task. Additionally, only five years of cost information is available in this document. The reports of the Military Procurement Priority Review Board have systems' priorities and costs, but generally not broken down by projects. The DCP's for each system have a great amount of information for the base case, but this model also requires four alternatives to the base. Consequently, should CARDBOMB be implemented, it is recommended that a RDTE System's Data Report be prepared and kept current. Besides being of great assistance to users of the model, it could prove to be an excellent planning document. A great deal of cost and effectiveness information on each system would be centralized, visible, and readily available for five alternative development plans. Such a document and the model itself, would no doubt be most efficiently maintained somewhere in the planning staff of OCRD, although its potential users might be personnel from the offices of the Director of the Army Budget, the Budget Review Committee, and the Assistant Vice Chief of Staff, in addition to OCRD.

B. OPTIONAL USER INPUTS

It is envisioned that this MIS would operate in a manner similar to the DEAN MACHINE system; i.e., the user-computer interface would be through a cathode ray tube (CRT) console. The user types in simple instructions and solutions are displayed

on a television screen before him. Some of these instructions are presented in this section.

Since the model is designed to handle alternative methods for altering the RDTE budget, (e.g., alter the budget constraint and do not consider slipping, fix the constraint and consider slipping, alter the time preference strategy, etc.) the computer program segment of the MIS must allow for the input of these options if it is to be efficient in terms of running time and storage space. Consequently, a user should have the capability of inputing any of the following options.

1. Select a time preference strategy. The most time consuming operation the program might be required to accomplish would be the construction of the TV_i versus cost curves, calculation of the marginal values (slopes), and the ordering of these slopes in decreasing sequence. It might therefore be desireable to have in storage, pre-constructed budget incrementing matrices for alternative strategies. A great deal of computer time could be saved this way. Therefore the following time preference strategy options might be made available.

   Option 1, a Short Range (a, b, c) Strategy, where the parameters are those determined "best" in the test of the model against the base case (Chapter 4, Section C).

   Option 2, Neutral (1, 1, 1) Strategy.

   Option 3, Long Range (c, b, a) Strategy, using the same parameters as Option 1, but in reverse order

   Option 4, User selects his own parameters. As has been stated, the analyst should not impose a strategy on the decision maker. Option 4 allows the user to input his own time preference parameters, but he should be made aware of the fact that the solution will take much longer to obtain.

2. Change any parameters? As familiarity with the model grows, the user may decide that he is not in agreement with some of the relative value, readiness date distributions or other parameters on file. Alternatively he may wish to test the sensitivity of a particular solution to some of the value, cost or other parameters. Here he is given the option to temporarily change any of the parameters he wishes. This could be accomplished by typing a code number (defined in Section C) to identify the parameters and the new value he desires to use.

3. Should the model consider slipping? A simple yes-no answer to this question would be sufficient to insure that the proper subroutines were used.

4. What fiscal year is being investigated? To answer this question the user types in the year. Although the development of the model dealt primarily with the first year (FY 73), any budget year can be investigated. Suppose for a particular FY 73 constraint the optimal solution resulted in a total FY 75 cost that was considered unreasonable. A constraint could then be imposed on FY 75 and the funding levels of systems be reduced until this new constraint is met.

5. Select the total RDTE budget constraint. The user would answer this question by typing in the dollar constraint he wishes to investigate.

6. Select the constraint for basic research. If this were the same as for the base case, the model would by-pass the subroutine designed to alter the Category 22 budget. If it were different, the model would calculate a new Category 22 budget according to the decision rules discussed in Chapter 4, Section G.

7. Select the constraint for management and support. The model does nothing with this other than to subtract if from the total constraint to determine how much is left for the remaining systems. Should this constraint be less than the base case, the difference would represent the user's personal judgement of the "organizational slack" that can be absorbed.

8. Select the output options. At this point the user informs the computer program what he desires to see in the way of output. Discussion of what these options might be is deferred to Section D of this chapter.

C. ORGANIZATION OF THE DATA INPUTS

A large number of data inputs are required for the use of CARDBOMB. How these are organized can have a significant effect on the efficiency of the computer program. Appendix B outlines the computer program and subroutines that would be needed for implementing the MIS in the fashion proposed in this chapter. As mentioned in the discussion on inputing strategy options, it has incorporated a trade-off of data storage for reduced running time. The following files would be required for operating the MIS in the manner proposed in Appendix B.

File 1, Budget Incrementing Matrix (BIM) for strategy option 1. The format for this pre-constructed matrix might be as was shown in Figure 7, page 56

File 2, BIM for strategy option 2. Same format.

File 3, BIM for strategy option 3. Same format.

File 4. Systems' Parameter File. In order to use strategy option 4 or to change some of the parameters, a file consisting of the inputs required for constructing TV_i versus cost curves is needed. Of course, this file is also necessary for constructing Files 1, 2 and 3. The format for this file might be as shown in Figure 14.

		[—— f=2 ——]										[—— f=3 ——			
		Total RDTE Cost	V	t_o	t_m	t_p	t'_o	t'_m	t'_p	a^1	a^2	a^3	Total RDTE Cost	V	t_o . . . .
System	1														
	2														
	3														
	.														
	.														
	.														
	.														
	.														
	n														

Figure 14. FORMAT FOR FILE 4

Note that a code (i,j) would be sufficient to identify the parameter that a user might wish to change.

File 5. Basic Research Projects. The mathematical operations used in investigating alternative Category 22 budgets are different than those for systems. Grouping these projects separately allows for the separate investigation of alternative basic research budgets. The format for File 5 could take the form of that shown in Figure 15.

		73	74	75	V	Total RDTE Cost	A
Project	1						
	2						
	3						
	.						
	.						
	n						

Figure 15. FORMAT FOR FILE 5

File 6, Yearly Budget Schedule. It may have been noted in the formats recommended for the other five files that neither annual RDTE nor total PEMA and OMA costs for systems were included. This, of course, could easily have been done. However since the user is only investigating one year at a time, collecting this data in a separate file can assist in saving core storage space. Figure 16 shows the format this file might take. Note that if the user were investigating the FY 73 budget, only the columns pertaining to that year would need to be called into core memory.

				[—— f=2	——]	[—— f=3	
		Total PEMA	Annual OMA	RDTE 73	RDTE 74	RDTE 73	RDTE 74 ...
System	1						
	2						
	3						
	4						
	.						
	.						
	.						
	.						
	n						

Figure 16. FORMAT FOR FILE 6

File 7, Financial Data File. Like the DEAN MACHINE, this model might be called upon to act as a "report generator", transforming cost data from one budget format to another. None of the files outlined thus far contain information on the costs (or identity) of the projects which compose the systems. This information could be included in File 7. Although Appendix B does not outline routines for incorporation of a report generation capability, this feature could be made a part of CARDBOMB.

D. RELATING COMPUTER OUTPUTS TO INFORMATION REQUIREMENTS

There are a number of capabilities of CARDBOMB that a user might wish to employ. Allowing him to select an output option insures that the proper subroutines are called and the particular information he is seeking is displayed. How much information is required at a given time would direct whether it would be best

displayed on the CRT or on a computer print-out. The following list of output options is not intended to be exhaustive. It might further demonstrate how the MIS could be used, however.

1. CRT display of changes from the base case. Normally a user would wish to focus his attention on the changes that resulted from his inputing a new parameter or budget constraint. This could be accomplished by a visual display of the new versus base funding schedules of the system or basic research projects which changed.

2. CRT display of changes from the last solution. It is envisioned that the model would be used in an iterative fashion, i.e., once a solution is generated with a certain set of parameters, the user might wish to employ another option to see how it affects this solution.

3. CRT Summary Display. The new and base funding schedules aggregated for each of the 22 categories might also be of interest.

4. CRT display of the 12 rows of the Budget Incrementing Matrix bracketing the total budget constraint. For a particular budget constraint the model recommends changes based on this matrix. The user might also wish to see what other changes would be recommended if the constraint were slightly greater or slightly less. Twelve rows are selected because of the 12 line output capability of the CRT.

5. Computer print-out of a Budget Incrementing Matrix. The BIM is an ordered list of increases to the budgets of systems as the total budget constraint is increased. Although it is only an approximation to the optimal solution, it could be used as a readily available planning document for answering the "What do you think we should do if the budget is cut" type question.

6. Print-out of the slip sequence list.

7. Print-out of the drop sequence list.

8. Print-out of detailed funding schedules of all systems at optimality.

9. Print-out of the complete RDTE budget in alternative formats.

VI. SUMMARY

Throughout this paper an attempt has been made to point out both the capabilities and limitations of the methods used in the model. CARDBOMB is not meant to be either a "cure-all" for the RDTE budgeting problem or the final answer for the contribution analytical models might provide. What the model can do is provide logical consistency between information gathered in the relatively "quiet" planning phase and the budget decisions made during the "crunch" period. Even during the "crunch" it is not envisioned that the solutions generated by the model should be arbitrarily accepted. However the budget feasible changes it recommends should serve to narrow the focus for a more careful investigation, one which might be well served by the comprehensive data bank.

A. CAPABILITIES AND LIMITATIONS REVIEWED

CARDBOMB has addressed individually the entire range of alternatives that can be employed for altering the RDTE budget. These were; increase or decrease the budgets of systems or projects, slip a system one or more years, add or drop a system or project from the program, and alter the RDTE budget total. Various analytical methods were used as noted below.

Based on subjective value judgements of category experts and cost data supplied by program managers, value versus cost curves were determined for each system. Then for a particular budget constraint, an algorithm was used to generate an approximation to the optimal RDTE budget. In this way trade-offs of value for cost were accomplished for each system, but considered as a part of the total rogram, not

as an individual system. By this approximation method increases or decreases to the budgets of systems are recommended. Basic research and exploratory development projects are recommended for reduction or increase based on a decision rule which insures that percentage increases (decreases) are applied to the budget of projects which are directly (inversely) proportional to their average values.

Dropping a system or project is also handled on an average value criteria. Because the model treats value interdependently and PEMA and OMA costs as negative value, its usefulness for assisting with this decision is limited. However it could be used to focus attention for further investigation on those systems with comparatively low average values.

When deciding whether or not a proposed system's development plan should be undertaken, the model can assist by identifying what needs to be given up in the RDTE program in terms of reduced funding levels for other systems. It can also help to identify the optimal funding level, i.e., the trade-off of cost for potential performance. Additionally, by comparing its average value with that of other systems, insight might be gained on whether or not the development plan should be undertaken.

The decision on whether or not to slip a system is handled by determining a yearly loss in value that would result, and recommending those systems for slipping whose loss in value is less than the gain that would be achieved by raising the funding levels of other systems.

It is hoped that the model could add insight into the "proper" total budget constraint by plotting a total value versus total budget curve in a budget interval around the historical percentage of the total Army budget. As mentioned in Chapter 4, the usefulness of this method is dependent on the shape of the resulting curve.

B. EXTENSIONS OF THE MODEL

Some of the limitations discussed above are limitations only to the extent that they were beyond the scope of this paper. The interdependence of value of the systems which cause the model to be limited in its application to the add and drop decisions have been discussed at length by Weingartner [ref. 9], and theoretical models in the general category of project selection are available which could be adapted to CARDBOMB. The treatment of costs, however, would have to be handled differently, i.e., PEMA and OMA uncoupled from the measurement of value. This would suggest that perhaps the real problem is not the optimization of the RDTE budget but rather the optimization of the RDTE, PEMA and OMA budgets combined. Techniques similar to those used in this paper could undoubtedly be applied in most cases to this vastly expanded model.

The average value decision rule for basic research projects, though intuitively appealing since it says to add the most money to those which are expected to return the most value per dollar, is not theoretically sound. The appropriate measurement for incremental changes in budgets is marginal value, not average value. A more thorough examination of Category 22 projects might suggest a more appropriate structure for modeling Basic Research.

Of course a very important extension of the model would be to implement it and see if it is useful in assisting in the RDTE budgeting problem. This would be a sizeable task that would no doubt be best accomplished in stages. For example very little would need to be changed in the computer programs for the final model if they were first written to accommodate the systems from only one category. Perhaps Category 5, STANOS, might be a suitable starting point since all these

systems come under a single program manager. Since the data manipulations for these few systems would not be excessive, the model could be tested without the use of the computer.

APPENDIX A
MATHEMATICAL CONCEPTS

This appendix is an extension of some of the concepts discussed in the main body of the paper. Details concerning these concepts were purposely omitted from the body of the text so that it would be more easily read by individuals not thoroughly familiar with the jargon of Operations Research. For those readers with an OR background, this appendix should assist in clarifying two important questions; what is embodied in the value parameters, and what is the formulation of the optimization program.

The concept of relative value as used in this paper is similar to that found in Fishburn [ref. 12]. Let V be a value function which maps a real number $V(s_{ij})$ to a system s_{ij} from the set of systems S_j in the j^{th} category. The survey respondent accomplishes this mapping considering

1. S_j

2. N_j; the set of all perceived needs for systems in the j^{th} category, where N_j is a function of,

3. E; the environment — his perception of the enemy threat, the range of possible scenarios, etc.

That is:

$$V(s_{ij}) = V[s_{ij}; S_j, N_j(E)]$$

With the usual convention that if s_{ij} is considered more valuable than s_{kj} then $V(s_{ij}) > V(s_{kj})$, the optimization methods used require that V be unique up to an increasing linear transformation. In other words, the results of the survey on the zero-ten scale must be considered to have established an interval scale of measurement, meaning that shifting the origin of the scale or multiplying it by a

positive constant will leave the relative lengths of the intervals between $V(s_{i,j})$ unchanged. For example:

$$\frac{V(s_{i,j}) - V(s_{k,j})}{V(s_{l,j}) - V(s_{m,j})} = \frac{aV(s_{i,j}) + b - [aV(s_{k,j}) + b]}{aV({}_{l,j}) + b - [aV(s_{m,j}) + b]} \qquad \text{for } a > 0$$

This requirement for an interval scale of measurement could be tested by surveying again to confirm that the zero-ten scale produces the same relative interval results as, for example, a zero-one hundred scale.

When the primary method (see page 29) is used to relate the value of each system to that of a program numeraire, the high-level DA managers are asked to use the "ranking-rating" method for each of the category numeraires. Thus they are being asked to map real numbers to the values of these systems considering:

1. $S_1, \ldots, S_{20}$; the sets of systems in each category.
2. S'; the set of numeraire systems.
3. $N_1, \ldots, N_{20}$; the set of needs in each category.
4. E; the environment

That is:

$$V(s_{q,j}) = V[s_{q,j}; S_1, \ldots, S_{20}, S', N_1(E), \ldots, N_{20}(E)]$$

Using the primary method for relating the value parameters of all the systems requires that the mapping $V(s_{q,j})$ should also result in an interval scale of measurement. The use of equation 2, page 29, is equivalent to finding "a" in the linear transformation, i.e., determining the constant

$$\frac{V_{q,j}}{V_{q,1}}$$

which compresses or stretches the value scale of the j^{th} category to make it commensurate with the scale of the program numeraire.

The secondary method, page 30, also seeks to determine

$$\frac{V_{q,j}}{V_{q,1}},$$

but in a different manner. To use equation 4, page 32,

$$\frac{N_j}{N_1}$$

must be determined by survey. The high-level managers must consider:

1. $N_1, \ldots, N_{20}$
2. E

The value function mapping is then:

$$V(N_j) = V[N_j; N_1(E), \ldots, N_{20}(E)]$$

All the value measurement methods discussed in the text also require the additivity assumption, i.e.,

$$V(s_{1,j} + s_{2,j} + \ldots + s_{i,j}) = V(s_{1,j}) + V(s_{2,j}) + \ldots + V(s_{i,j}) \quad \text{for } i=1, \ldots, n_j$$

For this assumption to hold, systems must be carefully defined. For example, a weapon and its platform must be one system. The assumption could be tested (with great effort) with surveys designed along the lines of the Churchman-Ackoff method for obtaining measures of relative value (see Burington [ref. 6, p. 26]). In brief, this would require that each pair of systems, then each triplet, etc., be tested by survey to insure that the additivity assumption holds.

Without any testing of the parameters obtained by the "ranking-rating" method, there is no way of insuring that consistent judgement has been applied in formulating the value function, V. In other words it must be presumed that the usual axioms for the existence of a real valued utility function hold, i.e., that the preference relation is reflexive, symetric and transitive. (See, for example, Fishburn [ref. 12,

p. 167]). The testing required to insure that the axioms hold would result in a very sizeable surveying effort, one which is felt by the author to be an unreasonable undertaking in practice due to the time that might be allotted. Eckenrode [ref. 13] has shown in a limited test of the rating method that no statistically significant differences in results were obtained from this method and some of the more complex ones which do test for compliance with the axioms. Of course his study has only limited relevance to this particular problem. Consequently, the parameters which result from the relatively simple methods outlined in the body of the text should not be viewed as being perfectly correlated with some "actual" real valued utility function for the Department of the Army. The sensitivity of a solution to the relative value parameters used should always be checked.

Algorithm 1, page 55, results from the formulation of the problem as a mathematical program in the following way.

We wish to find the optimal funding level $\bar{f}^0 = (f_1^0, f_2^0, \ldots, f_n^0)$ which maximimizes the total value of the program and satisfies the budget constraint for the year being investigated. That is:

Maximize: $g(\bar{f})$

Subject to: $h(\bar{f}) \leq B_t$

For the i^{th} system, the problem has been formulated as:

$$TV_i(x_i) = \sum_t d_t \cdot a_t \cdot p_t(x_i) \cdot V_i[x_i ; s_{i,j}, S_j, N_j(E)]$$

Although a separable programming approach is not the only formulation that might be considered, it does result in the simplest solution methods. For $g(\bar{f})$ to be a separable function it is necessary to assume that:

$$V_i[x_i , s_{i,j}, S_j, N_j(E)] = V_i(x_i)$$

that is, the value of the i^{th} system is independent of the values of all the others. As discussed in the text, it has been assumed that in the funding range [f = 2, . . . , f = 6] this independence of systems' value holds. "Very often the choice between independence or not is a choice between 'divide and conquer with approximations' or 'don't divide and don't conquer at all.' " Fishburn [ref. 12, p. 295]. However "don't conquer at all" is not quite the case with this problem. As has been stated, Weingartner [ref. 9] discusses a number of models that take into account the interdependence of value. Some of them would be appropriate for the "add" and "drop" decision and could be adapted to CARDBOMB.

With the assumption of independence of value, the program becomes:

$$\text{Maximize:} \qquad g(\bar{f}) = \sum_i TV_i(x_i)$$

$$\text{Subject to:} \qquad h(\bar{f}) \leq B_t$$

The budget constraint equation is logically separable into the year t budgets for each of the systems, i.e., $h(\bar{f}) = \sum_i C_{i,t}(f_i) \leq B_t$, where $C_{it}(f_i)$ is a discrete function in f, the five finding levels. The final mathematical program is then:

$$\text{Maximize:} \qquad \sum_i TV_i(x_i)$$

$$\text{Subject to:} \qquad \sum_i C_{it}(f_i) \leq B_t$$

$$f_i = f_{i,k} \qquad \text{for } k = 2, \text{ or } 3 \ldots \text{ or } 6$$

Algorithm 1 accomplishes this optimization by first calculating the marginal values, $s_{i,k}$, of raising the funding level from f = k to f = k + 1; i.e.,

$$s_{i,k} = \frac{TV_i(f_{i,k+1}) - TV_i(f_{i,k})}{x_{i,k+1} - x_{i,k}} \qquad \text{for } k = 2, \ldots$$

When the set of s_{ik} are ordered in decreasing sequence, iteratively increasing the funding levels according to this sequence insures that the increase has been added to the system with the highest gain in value per <u>total</u> RDTE dollar increase. However as was pointed out on page 54, this is not necessarily the optimal increase when a year t budget constraint is considered. Lacking information on these year t constraints for the out-years, the question becomes one of choosing a criteria; either maximize value considering the marginal value of total cost or the marginal value of year t cost. Of course Algorithm 1 uses the former criteria, but a user of the model might also wish to investigate a solution resulting from the latter. The two solutions would be identical if the percentage differences in total cost between each funding level were the same as the percentage differences in year t costs for all systems. In this case the sequence of $s_{i,k}$ would be the same as a sequence resulting from using $C_{i,f+1,t} - C_{i,f,t}$ in the denominator of the $s_{i,k}$ formula.

A number of nonlinear programming search techniques might be applicable to finding the global optimum for a particular year t budget constraint. Unfortunately until such time as data might be collected and the shape of the TV_i versus year t cost curves determined, it is impossible to predict how divergent the two solutions would be, or to recommend a particular solution algorithm. Of course if these curves were also concave in the region of positive value, using a sequence of marginal values of year t cost in Algorithm 1 would be a simple method.

APPENDIX B
CONCEPT FLOW CHART

This appendix is added to demonstrate the reasonably simple nature of the computer program that would be required to implement CARDBOMB. It is designed to give the reader a better understand of the MIS outlined in Chapter 5, not to present a detailed programming flow chart. Readers with some familiarity with programming may note that the computer operations required are neither complex or excessively time consuming.

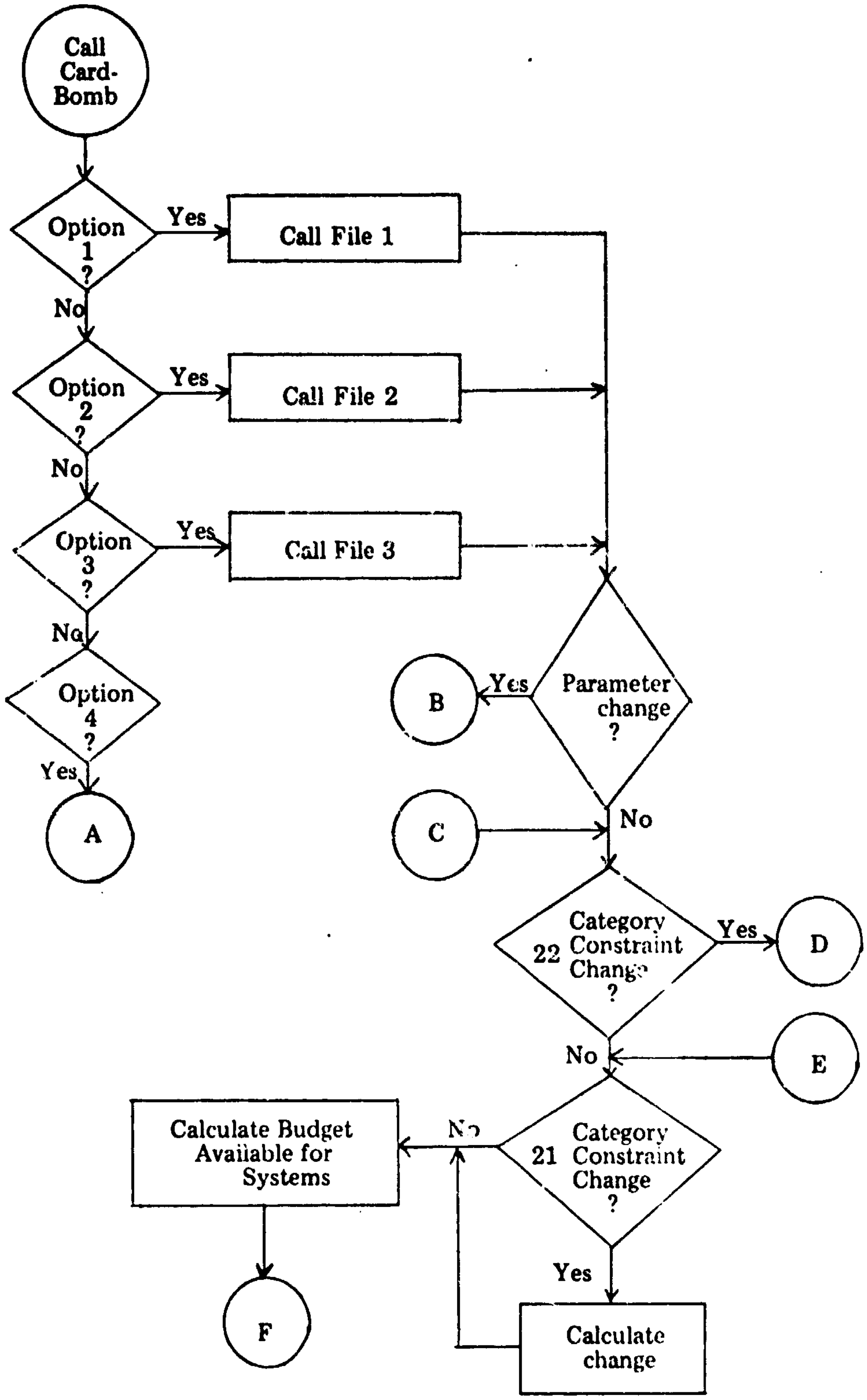

Figure 17. PRINCIPAL BRANCH OF THE PROGRAM

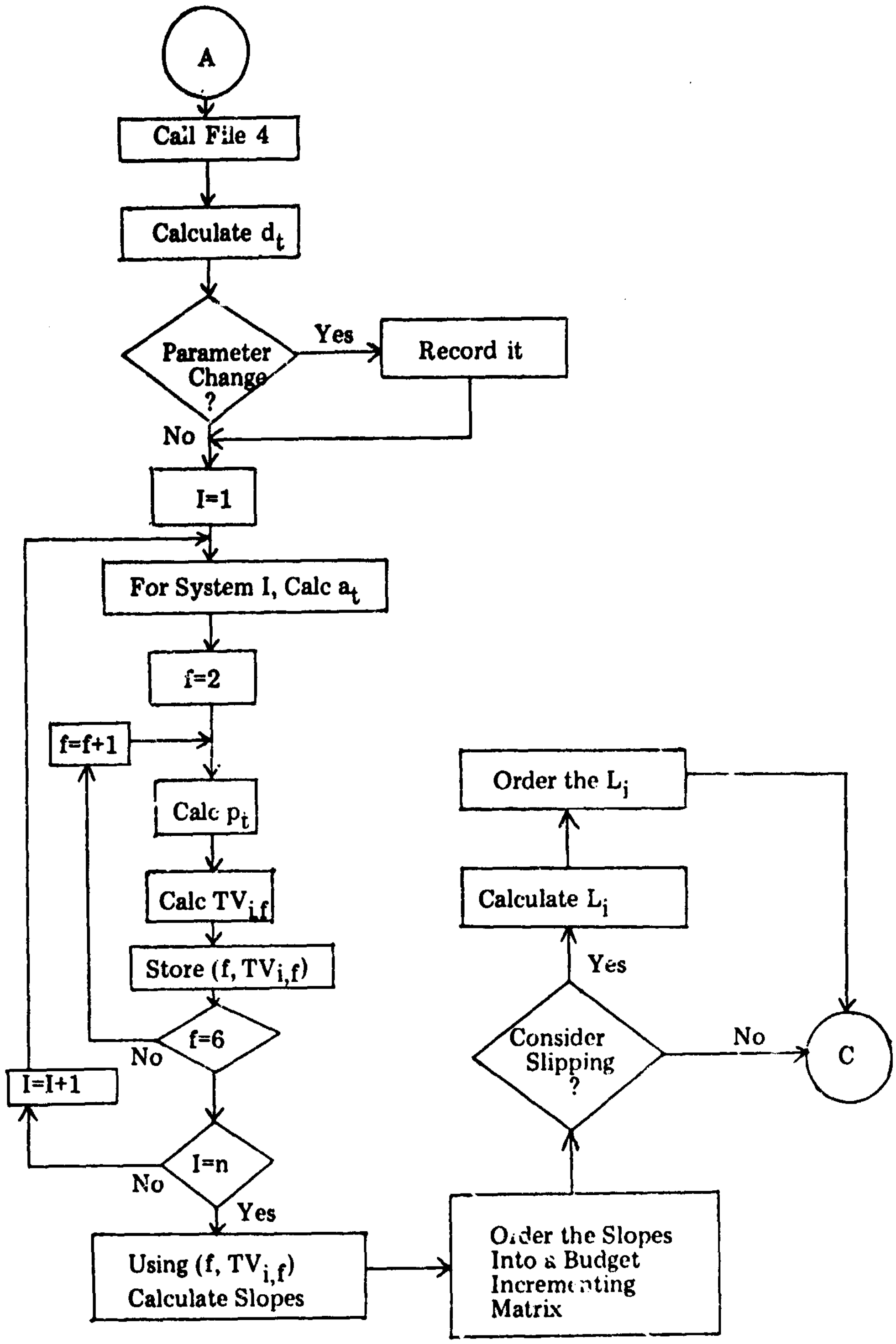

Figure 18. STRATEGY OPTION 4 SUBROUTINE

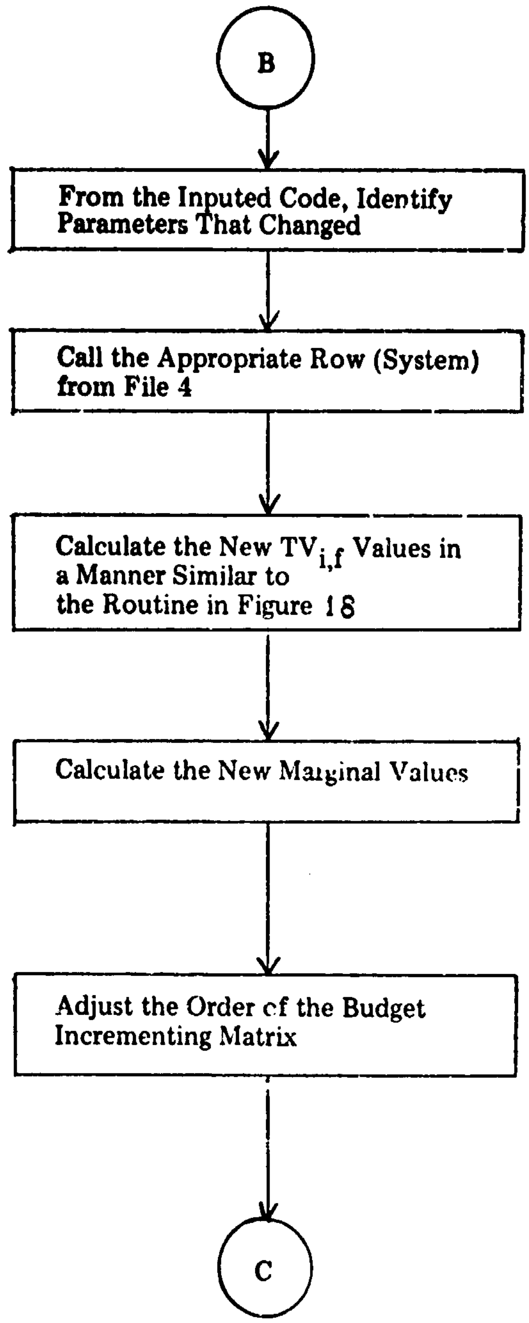

Figure 19. PARAMETER CHANGE SUBROUTINE

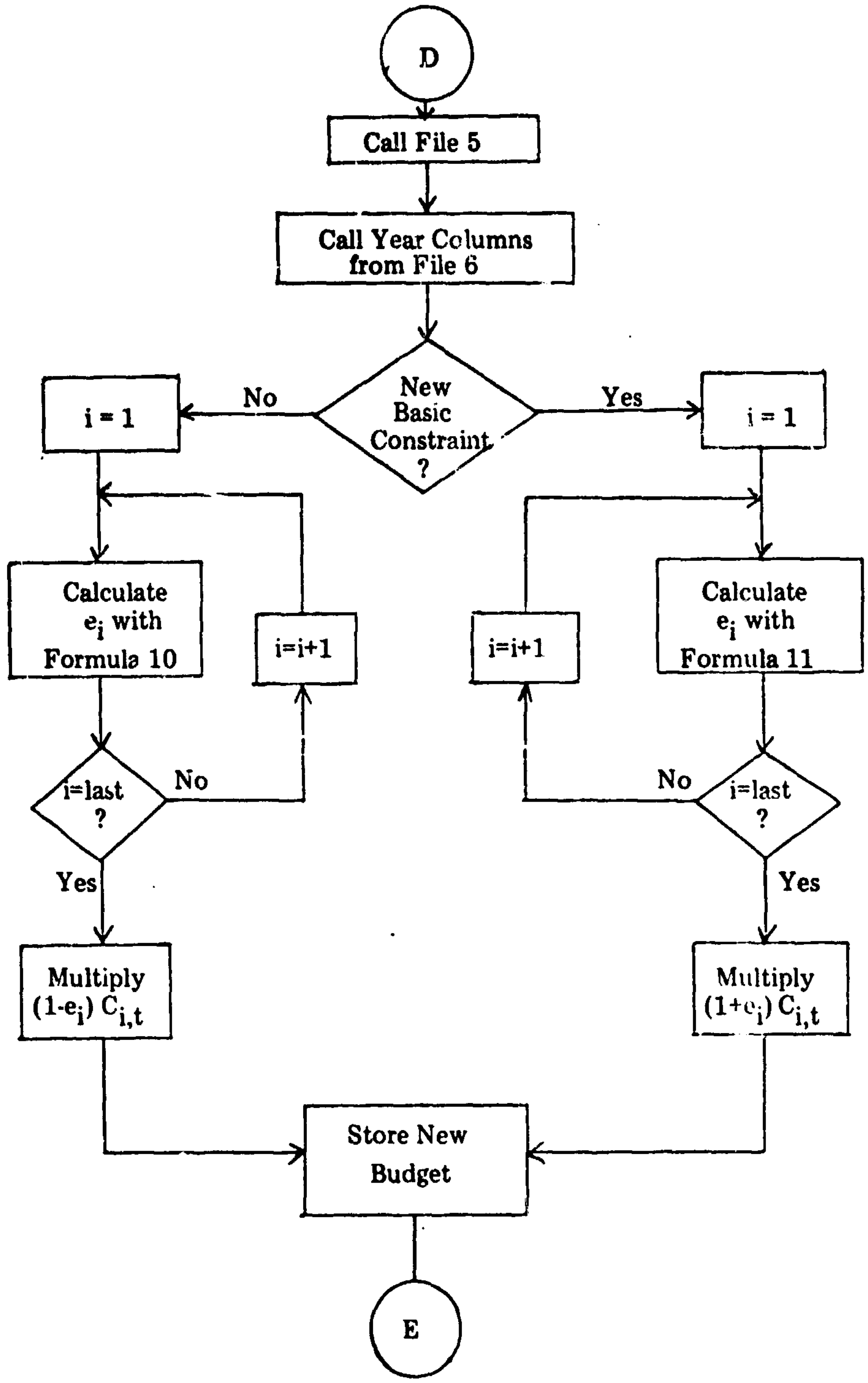

Figure 20. BASIC RESEARCH SUBROUTINE

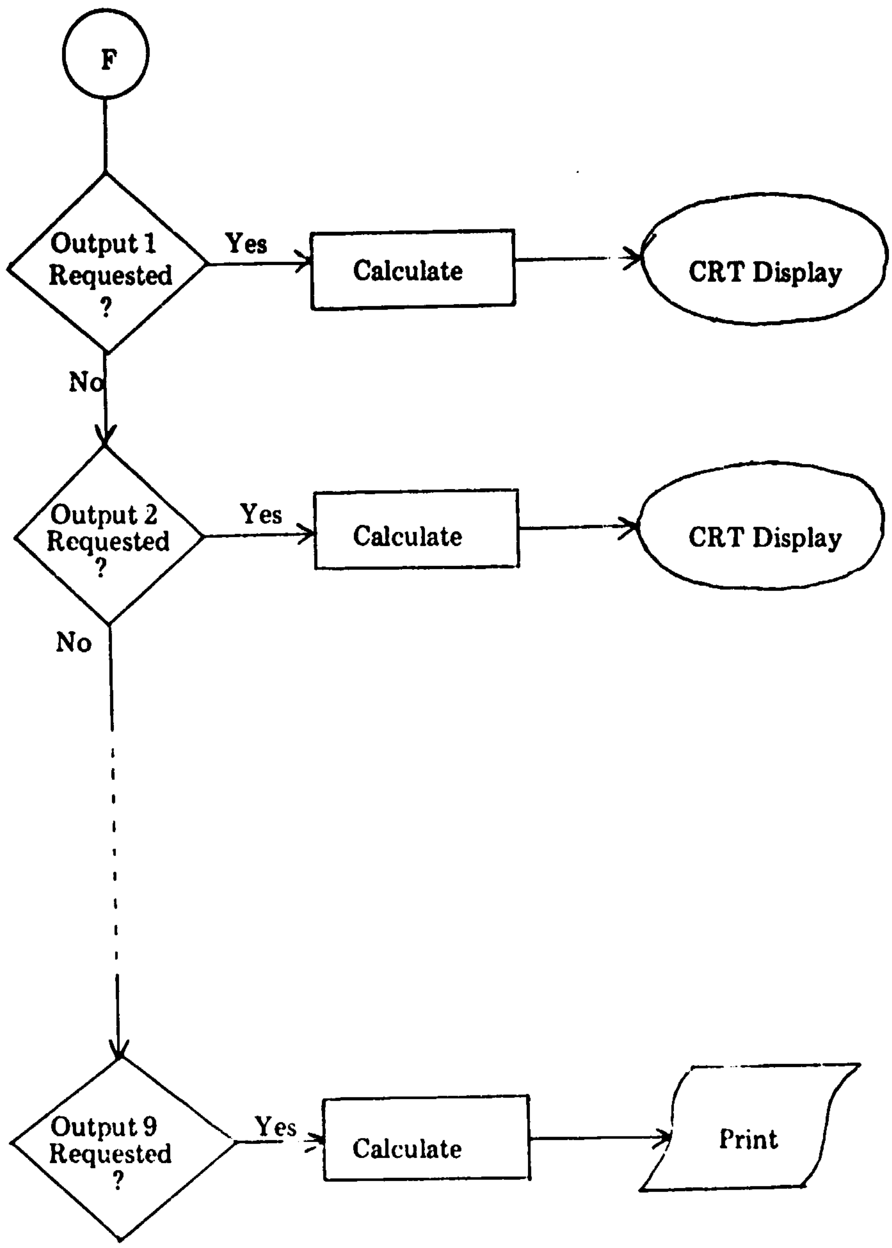

Figure 21. OUTPUT SUBROUTINE

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